

REOBSERVATION OF CLOSE QSO GROUPS: THE SIZE EVOLUTION AND SHAPE OF LYMAN ALPHA FOREST ABSORBERS¹

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ABSTRACT

In order to study the size and shape of the absorbers that lie in front of the QSOs, in particular the Ly α forest, we present an analysis of 785 absorption lines in the spectra of five QSOs in close groupings: a pair (LB9605: 1517+2357 at $z = 1.834$ and LB9612: 1517+2356 at $z = 1.903$, with a separation of 102 arcsec between them) and a triplet (KP 76: 1623+2651A at $z = 2.467$, KP 77: 1623+2653 at $z = 2.526$, and KP 78: 1623+2651B at $z = 2.605$, with separations of 127, 147 and 177 arcsec between pairs 76:78, 76:77 and 77:78, respectively). Both of these QSO groups have been observed before, but these data represent a drastic increase in signal-to-noise ratio and/or wavelength coverage over earlier data, and provide a qualitatively different view of the nature of the absorbers. The pair samples a scale critical in determining the size upper bound of Ly α absorbers, with significant leverage in redshift compared to previous studies. In the case of the triplet, this represents the spatially densest sample of Ly α forest absorbers ever studied, and an almost ideally-suited probe of the shape of absorbers. We observe a significant number of Ly α lines in common between the triplet sightlines, for lines stronger than rest equivalent width $W_o > 0.4\text{\AA}$ (and no detected metal lines) and velocity differences up to 200 km s^{-1} , corresponding to a two-point correlation function $\xi = 1.88^{+0.78}_{-0.50}$ on scales 0.5 to $0.8\ h^{-1}\text{ Mpc}$ with $\langle z \rangle = 2.14$, and inconsistent at the 99.999% level with the absence of any clustering. These data also show that a significant fraction of the $W_o > 0.4\text{\AA}$ Ly α forest absorbers span all three sightlines to the KP triplet, indicating that the strong-lined absorbers are consistent with nearly round shapes, chosen from a range of possible cylinders of different elongations. This may be inconsistent with results from hydrodynamic/gravitational simulations of H I in the early Universe indicating that the theoretical counterparts of Ly α forest clouds are

long and filamentary. Furthermore, there is a probable correlation of W_o with Δv suggestive of the clouds being flattened and expanding with the Hubble flow in their long dimension, as would be indicative of sheets or filaments. This is supported by the uniformity of linestrengths between the three sightlines, for $W_o > 0.4\text{\AA}$. We conclude, tentatively, that the $W_o > 0.4\text{\AA}$ Ly α forest objects are sheetlike. In contrast, the weaker lines, $0.2\text{\AA} > W_o > 0.4\text{\AA}$ show no evidence of spanning the sightlines of these groups, but have sizes significantly larger than the luminous portions of galaxies, and C IV absorbers as revealed by closer-separation QSO pairs. When the LB sightline pair is included with other pairs at different redshifts and sightline separations, one finds no evidence for evolution of Ly α absorber size with redshift. We also show that there is no evidence of large-scale structure in the Ly α forest consistent with ionization of H II by foreground QSOs as seen in the spectrum of background QSOs (the “foreground proximity effect”). Finally, we see a marginal detection of the sightline two-point cross-correlation function for C IV lines $\xi = 2.05^{+1.82}_{-1.21}$ over scales of 0.5 to 1 h^{-1} Mpc. This is significantly weaker than ξ measured by auto-correlation along single sightlines for $200 \text{ km s}^{-1} < \Delta v < 600 \text{ km s}^{-1}$, suggesting that most of the latter signal may be due to the internal motions within absorbers which are smaller than 0.5 h^{-1} Mpc.

Subject headings: quasars: absorption lines - intergalactic medium - cosmology: observations

1. INTRODUCTION

The past several years have seen rapid advances in our understanding of the Ly α forest. In part progress is based on the unprecedented spectroscopic capabilities of the Hubble and Keck telescopes, but advances have also been made using 4-meter class telescopes in measuring the size of the clouds. The size and shape is crucial in establishing the spatial number density of the cloud population, the ionization state of the clouds, their mass, and hence their contribution to the mass density of the Universe. Beyond more uncertain lensed QSO Ly α size limits (Foltz et al. 1984, Smette et al. 1992, 1995), the first definite indication of large absorber size came from observations of the 9.5 arcsec separation, $z = 2.050$ QSO pair 1343+2640A/B (corresponding to a sightline separation of 39-40 h^{-1} kpc proper distance, with $h = H_o/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_o = 1/2$), indicating a absorber radius of 100 – 200 h^{-1} kpc (Crotts et al. 1994, hereafter Paper I; Bechtold et al. 1994, hereafter Paper II; Dinshaw et al. 1994). Subsequent observations of a lower redshift pair Q0107-0234/0107-0235 ($z = 0.952, 0.956$, separation= 301 to 364 h^{-1} kpc proper distance) suggested an even larger absorber size, and at lower redshift (Dinshaw et al. 1995). A treatment of previously published, higher redshift pairs (Shaver & Robertson 1983, Crotts 1989, Elowitz, Green & Impey 1995) at separations larger than that of 1343+2640 revealed that absorbers must be either non-spherical, clustered, or drawn from a distribution that is non-uniform in radius (Fang et al. 1996 - Paper III), and also indicated the need for further data, either for these pairs or new ones (yet to be discovered). This approach is exploited in the current work, in §4.4.

The size of the absorbers implies that they contain a significant fraction of the baryons in the Universe (Fang & Crotts 1994, Rauch & Haehnelt 1996, Paper III). As such they might be analyzed in detail using hydrodynamic/gravitational simulations of the early Universe (Zhang, Anninos & Norman 1995, Katz et al. 1996, Miralda-Escudé et al. 1996).

Indeed, the size of the absorbers is key to identifying the corresponding objects in the simulations e.g. Cen et al. 1994, dealing with ~ 20 kpc proper diameter clouds, in contrast to Miralda-Escudé et al. 1996, dealing with clouds 100 kpc wide and 1 Mpc long. One outcome of these simulations is also the possibility of predicting the shape of the clouds, which can be compared to QSO triplet data to provide a crucial test of the models, in §4.5. Paper III also suggested that the shape of Ly α clouds might be studied directly using QSO triplets. We present a measure of the absorber shape using triple sightlines in order to facilitate this comparison.

Several theoretical papers have touched or even concentrated on structure on small scales in the Ly α forest as measured by double sightlines. Charlton, Churchill & Linder et al. (1995) suggest a number of tests sensitive to the shape of Ly α clouds probed by pairs of sightlines. These include a test of the correlation of the two neutral hydrogen column densities (N_{HI}) in the case where lines in different sightlines correspond in redshift, a test based on N_{HI} of the detected line in the case of an anticoincidence, where only one line is detected at a given redshift, and a method for learning about the velocity field in the clouds by measuring the velocity differences between sightlines. These tests are constructed for comparison to idealized models of cloud shape and kinematics. Miralda-Escudé et al. (1996) perform a detailed hydrodynamical/gravitational numerical simulation of collapsing structure and gas reaction. For sightline pairs passing through their model’s volume, they calculate a correlation coefficient describing the similarity of absorption between sightlines as a function of transverse spatial separation and line-of-sight velocity difference. Cen and Simcoe (1997) investigate the shapes of clouds within simulations like those of Miralda-Escudé et al., calculating the shapes of clouds at different density contrast levels as well as their effective size. They propose a test based on the correlation between velocity differences between coincident lines versus the sightline separation for pairs. They also present the spatial two-point correlation function for Ly α clouds of various

densities (and presumably linestrengths) and study the function’s redshift evolution, and consider statistics based upon whether absorption lines produced by sightlines passing through their model volume arise in identical or different clouds (which is difficult to test empirically in absorption spectra). Charlton et al. (1997) study model simulations (Zhang et al. 1995) analogous to Miralda-Escudé et alia’s and Cen and Simcoe’s. They compute size and shape measures analogous to those treated empirically in Paper III, including the variation of inferred spherical (or disk-like) cloud size as a function of pair sightline separation, and the related statistic of line coincidence/anticoincidence ratio as a function of sightline separation. They also recast the tests from Charlton et al. (1995) in terms in this simulation, as opposed to simplified cloud models. We will apply several of the preceding tests in §4.8, as well as others that we develop.

Multiple sightlines are also highly valuable in probing large scale structure, in that sightlines separated by transverse distances smaller than the structure should show large correlations with each other on these scales, since they pierce the same features. This remedies the problems of searching for voids with single sightlines (Carswell & Rees 1987, Crofts 1987, Duncan, Ostriker & Bajtlik 1989, Rauch et al. 1992), because multiple, well-sampled sightlines can provide a stronger test for voids by placing more absorbers in a void-sized volume than could possibly be obtained along a single sightline. We study this in §4.3. Furthermore, the effect of a foreground QSO upon the H I distribution in front of another QSO should be significant if the physics of the “proximity effect” (Bajtlik, Duncan & Ostriker 1989) is as simple as supposed. Some data exist on the foreground QSO proximity effect (Crofts 1989, Dobrzycki & Bechtold 1991, Fernández-Soto et al. 1995), but they are inconclusive and could easily be improved, as in §4.2. Finally, large scale structure can also be sought in the metal-line system distribution, and by cross-correlating multiple sightlines one circumvents the possible ambiguity between internal velocity structure due to motions within single absorber versus true spatial clustering of spatially distinct objects.

These problems are addressed in §4.9.

2. Observations

Observations of all five QSOs were performed using the RC Spectrograph and T2KB CCD on the Kitt Peak National Observatory’s four-meter telescope on UT 1995 June 1-4, using the BL-420 and BL-450 gratings in second order for the 3170-4720Å, 1.7Å FWHM resolution setup and 4450-5750Å, 1.4Å FWHM resolution setup, respectively. Wavelengths are reduced to the vacuum heliocentric frame. For the Q1623+2651A, 1623+2653, 1623+2651B data (KP 76, 77 and 78 respectively), spectrophotometric calibration was too uncertain to use. *Hubble Space Telescope* observations of 1517+2356/1517+2357 (LB 9605 and LB 9612 respectively) were made using the Faint Object Spectrograph G190H and G270H setups as part of program GO 5320 of Foltz et al. 1994. Data were also obtained on LB 9605 and 9612 UT 29-30 April 1992 by Elowitz et al. (1995) at the KPNO 4m/RC Spec at 3210-3590Å, and they kindly let us coadd their data with ours. This involved recalibrating the wavelength scale, as there appeared large shifts with respect to both the 1995 KPNO and *HST* wavelengths. This was accomplished in four ways: by re-identifying lines in the Th-Ar comparison spectrum accompanying the 1992 KPNO data, and by cross-correlating the overlapping portions of the QSO spectra in the *HST* and 1995 KPNO data with the 1992 KPNO data (and each other), as well as the night sky spectra from the 1992 and 1995 KPNO data sets. These show disagreements as large as 60 km s⁻¹, so that over the region 3270-3340Å the wavelength calibration might be uncertain by amounts as large as this. The resulting spectra, for KP 76, 77 and 78, are shown in Figures 1-3, and for LB 9605/9612 in Figures 4-5.

3. Analysis

Continua were calculated and lines detected, de-blended and assigned identifications according to Crotts (1989). Deblending was performed using multiple gaussian fits instead of Voigt profiles in nearly all cases, with the exception of resolved lines. We use a lower than usual S/N cutoff of 3.5σ for line detections. We are confident of this approach because we are able to check our results for KP 77 against a high S/N Keck HIRES spectrum of the object, the highest S/N part of a larger sample collected for the triplet (Crotts, Burles & Tytler 1997). At a 3.5σ cutoff for the KPNO data, no false detections are found over the 3900-5700Å overlap between the two data sets. In fact the KPNO 4m observations do a good job of detecting all obvious lines in the Keck spectrum (except for some very weak lines in the red KPNO 4m spectrum past 4700Å), while, of course, not resolving very close lines. We are fairly confident of our linelists, therefore, and expect approximately four lines out of our 785 to be false detections due to statistical fluctuations.

3.1. Absorption Line Identification

We try to be complete as possible in identifying metal-line systems, since stray metal lines might contaminate the statistical properties of Ly α samples, particularly if metal-line systems are redshift correlated. We follow the procedure of Crotts (1989) and list all “definite”, “probable” and “possible” systems (the later denoted by “?”) thereby dividing the systems into classes by probability of being reproduced in a random linelist having the same global distribution as real QSO absorption lines.

We identify the following metal-line and Lyman series absorption line systems, detailed in the linelists (Tables 1-5) and listed by QSO below.

KP 76:

This QSO is surprisingly lacking in absorption lines and systems. Only two well-established metal-containing systems are seen:

$z_{ab} = 2.11226$.– This system shows strong Ly α , C IV and Si III, as well as a firm Si IV doublet, plus Si II $\lambda 1260$ and C II $\lambda 1334$. Four of these eight lines occur beyond the Ly α forest.

$z_{ab} = 2.24563$.– Very strong Ly α and Ly β compose this system, along with weak C IV $\lambda 1548$, Si III and C I $\lambda 1277$. Ly α is significantly offset from the other lines, suggesting that it is contaminated by another line.

$z_{ab} = 1.93778?$, $2.40484?$ and $2.44125?$.– KP 76 shows two Ly α /Ly β pairs at $z = 2.40484$ and 2.44125 , both with much weaker associated Si III $\lambda 1206$, but no detected C IV. There is a similar system at $z = 1.93778$, but Ly β is below the short wavelength limit.

KP 77:

$z_{ab} = 0.88720$.– This is a strong system marked by many lines redward of the Ly α forest. It is peculiar that the Mn II lines are offset several hundred km/s from the five Fe II and four Mg II and Mg I lines. The Mg II doublet is mixed into a complex of structure near 5285\AA , but is the strongest contribution to this complex.

$z_{ab} = 2.40060$.– Ly α is strong, as is C IV in this system, although the 1550\AA line is confused with the Mg II doublet at 0.88720 . Weaker Ly β , Si III $\lambda 1206$ and a possible O VI doublet also support the system.

$z_{ab} = 2.40602?$ – Further structure in the complex at 5285\AA is explained by a C IV doublet at $z_{ab} \approx 2.406$. A strong Ly α line sits at slightly higher redshift.

The exact redshift of this system will benefit from higher resolution data on the complex mixing this and the last two systems.

$z_{ab} = 1.87952, 1.97331, 2.05050, 2.05380, 2.16128, 2.24455$ and 2.52900 .– These are all examples of C IV doublets appearing redward of the Ly α emission line, accompanied by strong Ly α at the same redshift. The $z_{ab} = 1.97331$ system also shows possible Si III $\lambda 1206$. The $z_{ab} = 2.053$ C IV doublet’s redshift sits on the blue wing of the corresponding Ly α line. The C IV doublet at $z_{ab} = 2.1616$ is blended with other lines, hence less certain. The $z_{ab} = 2.52900$ system is at high enough redshift so that Ly β is also detected, and possible Fe lines.

$z_{ab} = 2.44490$ and $1.67130?$ – These are Lyman series systems with weak C IV $\lambda 1548$. The $z_{ab} = 2.44490$ system is more definite having Ly β and possible Ly γ as well as Ly α (the only Lyman series line at $z_{ab} = 1.67130$ appearing above the short wavelength cutoff).

$z_{ab} = 2.40966?, 2.46345?$ and $2.47424?$ – These are strong Ly α /Ly β pairs, without other supporting lines.

KP 78:

$z_{ab} = 2.09428$.– This is a very strong, probably damped, Ly α absorber with strong detections of the C IV and Si IV doublets, Si III $\lambda 1206$, C II $\lambda 1334$, weaker Al II $\lambda 1670$ and probable contributions from Si II $\lambda 1260$ and Fe II $\lambda 1122$. The Ly α centroid is offset about 80 km/s from the other lines.

$z_{ab} = 2.23925$.– This system is defined by strong C IV and Si IV doublets as well as C II $\lambda 1334$, plus possible contributions from C I $\lambda 1277$ and Fe III $\lambda 1122$. It shares a strong Ly α line with the $z_{ab} = 2.24173$ below.

$z_{ab} = 2.24173$.– As well as very strong Ly α and C IV, this system shows C I $\lambda 1277$, C II $\lambda 1334$, the N V doublet, Si IV $\lambda 1393$, Si III $\lambda 1206$, the strongest lines of Si II (1260Å, 1304Å and 1190Å), plus possible Fe III $\lambda 1122$.

$z_{ab} = 2.55106$.– This system shows strong Ly α , β and γ , Si III and weak C IV $\lambda 1548$, Si IV $\lambda \lambda 1393$, 1402 , Si II (1260\AA , 1304\AA and 1190\AA) and possible C II $\lambda \lambda 1036$, 1334 , C III $\lambda 977$ and Fe III $\lambda 1122$.

$z_{ab} = 2.57482$.– There is no C IV detected but moderate Ly α , β , γ and δ . Also possible are Si III, Si IV $\lambda 1393$, Fe III $\lambda 1122$ and Fe II $\lambda 1144$.

$z_{ab} = 1.98490$, 2.04240 and 2.09592 .– These are all C IV doublets outside of the Ly α forest, plus strong Ly α lines. The $z = 1.98490$ system also contains Ly β . The redshift 2.09592 system shares Ly α with 2.09428 above and probably also shows Si III.

$z_{ab} = 1.93770?$ and $2.06117?$ – These are possible systems consisting of weak C IV $\lambda 1548$ outside of the forest plus strong Ly α .

$z_{ab} = 2.36526?$, $2.42738?$, $2.44138?$, $2.45570?$, $2.45801?$, $2.53649?$, 2.53941 , $2.54356?$, $2.54879?$, 2.56715 and $2.59458?$ – These are “possible” and probable Ly α , β pairs. The $z_{ab} = 2.53941$ and 2.56715 also show Ly γ . The 2.59458 system is only suspected. If this line is Ly α , one should expect to see Ly β at 3687.04\AA . There is a marginally detected line there, at about $W_{obs} = 0.3\text{\AA}$, so this is plausibly consistent with 4369.82\AA being Ly α .

LB 9605:

$z_{ab} = -0.00055$.– This Galactic system is marked by the Mg II doublet, Ca II $\lambda 3934$, Mg I $\lambda 2852$, Al II $\lambda 1670$, the four strongest lines of Fe II, two of Fe I and three of Mn II. Note that a similar system is seen in LB 9612.

$z_{ab} = 0.73825$.– This is composed of Ly α , β and γ , plus the C IV doublet and Si IV $\lambda 1393$. All of these lines fall in the forest but appear to be unambiguous.

$z_{ab} = 1.02780$.– This shows Ly α , β , γ and δ , the C IV doublet, Si IV $\lambda 1393$, Si II $\lambda 1206$, C III $\lambda 977$ and a likely O VI doublet. Most of these lines are blended with components of

other systems, and none land beyond the forest. (None would be expected.)

$z_{ab} = 1.51350$.– A weak C IV doublet lands outside the forest, while the other lines consist of Ly α , probable Ly β , Si II $\lambda 1260$, C I $\lambda 1277$, and possible Fe II $\lambda 1144$, Fe III $\lambda 1122$ and the O VI doublet.

$z_{ab} = 1.59590$.– This is a strong system consisting of the first ten Lyman series lines plus C IV $\lambda 1548$. The absence of a Ly limit feature ($\tau < 0.1$) implies $N_{HI} \lesssim 1.5 \times 10^{16} cm^{-2}$.

$z_{ab} = 0.41063$.– This is a probable C IV doublet in the forest associated with a strong Ly α line.

$z_{ab} = 1.19268$.– This is a probable Ly α /Ly β pair with a C IV $\lambda 1548$ line beyond the forest.

$z_{ab} = 1.80465$.– Another strong system of the first seven Lyman series lines, it shows no metal lines.

$z_{ab} = 1.01602, 1.07973, 1.30150, 1.60295, 1.68573, 1.72400?, 1.84560$.– These consist of at least the first three Lyman series lines in a pure hydrogen systems. Additionally, one finds Ly δ for 1.30150, 1.60295, 1.07973 and 1.84560, and Ly ϵ for 1.07973. There is a possible C IV $\lambda 1550$ line at $z_{ab} = 1.30142$. The $z_{ab} = 1.72400$ system is more uncertainty due to ambiguity in some of its line identifications.

$z_{ab} = 0.70010?, 0.96730?, 1.16401?, 1.19274?, 1.42858?, 1.55105?, 1.58226?, 1.62531?, 1.68137?, 1.70001?, 1.73948?, 1.74690?, 1.75165?, 1.77245?, 1.78948?, 1.82251?$ – These are possible Ly α /Ly β pairs; all have strong Ly α . The 1.82251 and 0.96730 systems also show Si III $\lambda 1206$.

LB 9612:

$z_{ab} = -0.00040$.– Like LB 9605, this spectrum shows a strong Galactic system. It includes the Ca II and Mg II doublets, Mg I $\lambda 2853$, Ca I $\lambda 2722$, Fe I $\lambda 2523$ and three strong lines of

Fe II (2382Å, 2586Å and 2600Å). Fe I λ 2484 is lost in the Ly break at 2484Å.

$z_{ab} = 0.25155$.– Another possible low-redshift system consists of the Mg II doublet and Mg I λ 2852, all in the forest.

$z_{ab} = 0.73690$.– This consists of Ly α , β , γ and a C IV doublet, all in the forest.

$z_{ab} = 1.05998$.– This system contains C IV and Si IV doublets, Ly α and β , and possible C I λ 1656.

$z_{ab} = 1.12625$.– This shows Ly α , a C IV doublet, Si II λ 1393, C I λ 1656 and possible N V λ 1238, Si III λ 1206 and C I λ 1277.

$z_{ab} = 1.30090$.– This probable system contains Ly α , β and C III λ 977 confused with other systems, Si II λ 1260 and, outside the forest, C IV λ 1548.

$z_{ab} = 1.41451$.– This is marked by strong Ly α , a C IV doublet (outside the forest) and a Si IV doublet.

$z_{ab} = 1.42671$.– This consists of a strong Lyman series to Ly 8, plus C IV λ 1548. The system's Ly β occurs at the Ly break at 2484Å. Ly 6 at 2258Å is marginally detected.

$z_{ab} = 1.55414$.– This includes Ly α , Ly β , a C IV doublet and C II λ 1334.

$z_{ab} = 1.72398$.– This is a very strong system with Lyman series lines up to at least Ly 10, and probably includes a blend of higher terms in the series. These are associated with a $N_{HI} \approx 4 \times 10^{17} \text{ cm}^{-2}$ determined from the Ly limit drop. Metal lines include C IV λ 1548, C III λ 977 and C I lines (1277Å and 1656Å).

$z_{ab} = 1.88690$.– In addition to a Ly series extending to Ly 10 and a Ly limit break corresponding to $N_{HI} \approx 1 \times 10^{17} \text{ cm}^{-2}$, this system shows Si III λ 1206, C IV λ 1548 and possible C III λ 977 and O VI λ 1031.

$z_{ab} = 1.75930$ and 1.79961 .– These are two Ly series systems extending to Ly 7 and Ly ϵ , respectively.

$z_{ab} = 1.43510?$, $1.43964?$, $1.62398?$, $1.64890?$, $1.70809?$ and $1.71516?$ – These are possible Ly α /Ly β pairs.

Both LB 9605 and LB 9612 have significantly more identified redshift systems per unit z than KP 76, 77 and 78, probably due to the greater wavelength coverage of these two spectra. Many of these systems would be unlikely to be recognized in the KP spectra. The consequences of this will be discussed in the next subsection.

3.2. Lyman Alpha Line Sample

Despite the large number of lines detected at wavelengths shorter than Ly α emission in LB 9605 and 9612, relatively few are due to unadulterated Ly α absorption, at least below certain wavelengths. This is particularly true for LB 9612, which suffers a nearly complete loss of flux below 2490\AA due to one Ly limit system, and a significant drop below 2670\AA due to another. Equally serious, however, is the contamination of a large stretch of spectrum by higher Ly series lines and metal lines, many associated with these two Ly limits. Of the 45 lines between 2490\AA and 2900\AA , only six are explained by uncontaminated Ly α lines, whereas above 2900\AA only 29% of the lines in the forest can be explained (even in part) by lines other than Ly α . Similar behavior, although not so drastic given the absence of Ly limit systems, is seen in LB 9605. This implies that the only useful sample of Ly α lines for comparing the Ly α distributions in LB 9605 and 9612 is in the wavelength range $2900\text{--}3445\text{\AA}$ ($z = 1.39$ to 1.83 , with $\langle z \rangle = 1.62$), roughly the range between Ly β and Ly α emission. (In practice, we use observed wavelength 2900\AA to the wavelength 1220\AA in the reference frame of the QSO, accounting for infall towards the QSO by up to 1000 km s^{-1} .)

We apply a similar constraint to the KP 76, 77, 78 triplet. In practice we consider those lines with wavelengths of 1020Å to 1220Å in the reference frame of the QSO, unless explicitly stated otherwise. While their spectra below Ly β emission are not so obviously contaminated by non-Ly α lines, this might be due to our ignorance of further metal-line systems because of the smaller wavelength coverage in these spectra compared to the LB pair. The Ly β to α emission line range from above constrains these samples such that all three overlap for redshifts 2.02 to 2.48.

For lines at redshifts lower than $z = 2.02$, the sensitivity of our data is also declining, but for some purposes, sensitivity cutoffs as large as $W_0 = 0.4\text{\AA}$ are useful. Also, for some purposes, we might be less worried about metal-line contamination, especially since we show that the metal-line system redshifts are weakly correlated between sightlines. In a limited number of specified cases, we impose a cutoff at $\lambda = 3350\text{\AA}$ (or $z = 1.756$), below which the sensitivity in KP 78 drops below $W_0 = 0.4\text{\AA}$. Given a line-of-sight number density evolution $N(z) \propto (1+z)^\gamma$, with an assumed $\gamma = 2.1$ (see §4.3), we study an average $\langle z \rangle = 2.25$ for the generally-used restrictive sample, and $\langle z \rangle = 2.14$ for the less-used, larger redshift range.

We take as Ly α lines all those between the wavelengths listed above and not otherwise identified as a metal line (although they can be the Ly α component of a metal-line redshift system). This is the “pure” Ly α sample. The “contaminated” sample is one in which a detectable contribution is suspected from a metal line from another redshift system, but the presence of a Ly α line is inferred from the strength of the actual line above that of the inferred metal line.

For unresolved Ly α lines in the KP triplet sample, then, the completeness cutoff (the 3.5σ threshold plus another 2σ to assure completeness) in each 1020-1220Å region is about $W_o = 0.19, 0.09$ and 0.15\AA , respectively. For LB 9605 and 9612, the sample reaches $W_o \approx 0.12$ and 0.13\AA , respectively (except for a small interval $1.691 < z < 1.768$ for LB

9605, where the threshold is as high as 0.4\AA), with the same caveats regarding uncrowded and unresolved lines. In some of our treatment below, we will discuss thresholds as low as $W_o = 0.1\text{\AA}$, knowing that this falls slightly short of our completeness condition, but most interesting results apply to cutoffs of $W_o = 0.2\text{\AA}$, 0.4\AA , or higher. The sensitivity of the spectra and our various Ly α samples are further described in Table 6.

4. Results

These higher quality data allow us to improve several unique measurements made in Crotts (1989) using the KP triplet, plus several new tests that we apply for the first time. Sections 4.1 through 4.3 deal with tests originally developed for the triplet in Crotts (1989) and section 4.4 applies cloud size techniques developed in Papers II and III to the LB pair for the first time, as well as the improved triplet data set. For this reason we reserve detailed discussion of techniques for section 4.5 and later, and refer the reader to these previous papers for earlier developments.

4.1. Ly α Velocity Cross Correlation

Following Crotts (1989), we can compute the spatial two-point function of Ly α absorbers by cross-correlating in velocity the distribution of Ly α lines (“pure” and “contaminated”). The resulting pairs are binned at 50 km s^{-1} intervals with cutoffs of, alternately, $W_o > 0.1, 0.2, 0.4$ and 0.8\AA . For the triplet (all three sightline pairs summed together) and the pair, the resulting cross-correlation pair count as a function of velocity difference Δv is shown in Figures 6a and 6b, respectively. For the triplet, the $\langle z \rangle = 2.25$ sample is shown.

In Figure 6a for the triplet, there is no apparent structure for weaker lines e.g. samples

with cutoffs at $W_o = 0.1\text{\AA}$ or 0.2\AA , but structure is apparent for lines with $W_o > 0.4\text{\AA}$ or 0.8\AA . For $W_o > 0.4\text{\AA}$, there are an average of 2.97 pairs per 50 km s^{-1} bin in the first 3000 km s^{-1} of Δv (and 2.83 per bin over $3000\text{ km s}^{-1} < \Delta v < 6000\text{ km s}^{-1}$), so that the appearance of eight pairs (or more) in the first 50 km s^{-1} bin as a random fluctuation is ruled out at the 99.0% level. (This is the Poisson confidence level for excluding the hypothesis that there is no intrinsic excess in the first bin, as might be substantiated by larger samples.) There are also 20 pairs in the first 200 km s^{-1} , which is ruled out as a random fluctuation at the 98.4% level. Thus there is evidence for a cross-correlation signal in the smallest velocity bins for pairs of $W_o > 0.4\text{\AA}$ lines, at about the 2.5σ level. This can be described by a two-point correlation function, averaged over proper separations of 496 to $720\text{ h}^{-1}\text{kpc}$ and with $\langle z \rangle = 2.25$ of $\xi = 0.72_{-0.38}^{+0.48}$ (68% confidence limits - *not* directly translatable into gaussian standard deviations for such a small sample). For the extended, $\langle z \rangle = 2.14$ sample, the clustering signal is stronger, both in magnitude and statistical significance: 29 pairs in the first 200 km s^{-1} bin versus 15.6 expected, implying $\xi = 0.86_{-0.28}^{+0.41}$, inconsistent with $\xi = 0$ at the 99.92% level. When only “pure” Ly α lines are considered, there are 26 in the first bin with 11.7 expected, implying $\xi = 1.23_{-0.36}^{+0.53}$, inconsistent with zero at the 99.991% level.

How important is the elimination of all Ly α lines with associated metal lines at the same z ? We did this for the extended, $\langle z \rangle = 2.14$ sample and found 21 pairs in the first 200 km s^{-1} bin versus 7.3 expected, giving $\xi = 1.88_{-0.50}^{+0.78}$, which is inconsistent with the no-clustering hypothesis at the 99.999% level. Hence, the exclusion of the metal-containing systems makes the signal marginally stronger.

There is a weak signal for larger Δv and stronger lines. Nine $W_o > 0.8\text{\AA}$ pairs land within $\Delta v < 600\text{ km s}^{-1}$ versus the mean expectation of only 3.6, a result expected in only 1.2% of random cases. Both of these results, for $W_o > 0.8\text{\AA}$ and 0.4\AA lines, are very similar

to results found by Crofts (1989) for a significantly smaller sample.

For the LB pair, the results are less impressive. For $W_o > 0.4\text{\AA}$, there are no pairs in the first 50 km s^{-1} bin, and only three pairs in the first 200 km s^{-1} versus a mean expectation of 1.9. In the first 300 km s^{-1} , there are six pairs versus 2.8 expected, which is ruled out as being random at only the 93.5% level. There is a larger excess in the $W_o > 0.2\text{\AA}$ sample, nine pairs versus 6.0 mean expectation in the first 200 km s^{-1} , but it is even less statistically significant.

We conclude that the $\Delta v < 150 - 200 \text{ km s}^{-1}$ cross-correlation signal obvious in Paper III, Figure 4 for QSO pairs closer than $400 h^{-1} \text{ kpc}$ persists to over $700 h^{-1} \text{ kpc}$ in the KP triplet, despite the weakness of the signal seen in the LB pair at separation $S \approx 430 h^{-1} \text{ kpc}$.

4.2. Large Scale Structure in the Ly α Distribution

As discussed in Crofts (1989), the distributions of the three Ly α forests in the triplet can be combined into a single probe of structures much larger than their sightline separations of $0.5\text{--}0.7 h^{-1} \text{ Mpc}$. These are constructed by running bins of different widths along complete Ly α line lists, counting the number of lines in each bin. The results are shown in Figures 7a and 7b for the $W_o > 0.4\text{\AA}$ and $W_o > 0.1\text{\AA}$ samples, respectively. The bin width alternates between 15, 30 and $45 h^{-1} \text{ Mpc}$ (for $q_o = 1/2$) and the bin center is stepped in redshift every $1/4$ of the bin width. In Figure 7a, two prominent underdensities occur, one at $z = 2.08$ and another at $z = 2.37$; from the bin width plot in which they are most prominent, they appear to have widths of about 15 and $30 h^{-1} \text{ Mpc}$, respectively. How statistically significant are they? The first dips to zero counts when the mean is 4.5 and represents one bin among 15 independent bins across the total redshift range, leading to an

a priori probability of finding a void this marked at about the 17% level due to random fluctuation. The $z = 2.37$ feature drops to a count of three versus an average of eight in one $30 h^{-1}$ Mpc bin (versus seven independent ones), for an *a priori* probability of 30%.

Note that these features are of roughly the same size as underdensities seen toward other QSOs: 0420-388 (Crofts 1987, Rauch et al. 1992) and 0302-0019 (Dobrzycki & Bechtold 1991). Note that the same sort of plot for $W_o > 0.1\text{\AA}$ line (Fig. 7b) shows no new features and the previously mentioned underdensities are washed out. If such structures are real, they are traced more by the stronger lines, in a way similar to the small scale structure seen in §4.1.

Neither of these features is significant enough to stand by themselves as a detection. It is interesting nonetheless to ask if they are associated with foreground QSOs, as might be expected if several bright QSOs sit in the foreground of this triplet and thereby destroy the neutral hydrogen at their redshift, or, if voids might exist as in the galaxy distribution, bounded by walls of more condensed objects, such as QSOs, perhaps. A search of recent QSO catalogs (e.g. Hewitt & Burbidge 1993) reveals one faint, possible QSO (KP 70) at $z = 2.1(?)$ and another at $z = 2.4(?)$ (KP 73). Both have $V \gtrsim 20$ and sit too far from the triplet in the sky (angular distances corresponding to about $6 h^{-1}$ Mpc and $3 h^{-1}$ Mpc proper separation, respectively) to be likely causes for such large voids (unless the flux we see is not representative of the flux experienced by observers in other directions, either due to variability of the QSOs or anisotropic radiation patterns). These do not seem likely to produce such underdensities due to a foreground QSO proximity effect; for this reason we are searching for other QSOs in the field (Crofts 1998).

4.3. Foreground QSO Proximity Effect

A more direct approach (Crotts 1989, Bajtlik et al. 1988 with correction found in Crotts 1989) to estimating the effects of QSOs on the absorbers along the sightlines to background sources is to compute the radiation field from the known, bright QSOs in the foreground and their effects on neutral hydrogen in their vicinity. This can be compared to the actual number density of lines seen towards the three background QSOs in the triplet, and the model can thus be tested. Over the relevant redshift range of interest (see Table 7), all QSO spectra are sensitive to $W_o = 0.1\text{\AA}$. These foreground QSOs include the triplet and the $z = 2.183$, $V = 19.6$ QSO KP 79, sitting about $1.2 h^{-1}$ Mpc in proper distance to one side (closest to KP 77 and 78). We make the assumption that the Ly α clouds are distributed uniformly except for the general evolution of line-of-sight number density with redshift, $n(z) = N_*(1+z)^\gamma$, where only lines with $W_o > 0.1\text{\AA}$ are counted, $\gamma = 2.1$ (intermediate between two recent determinations: Bechtold 1994, Lu, Wolfe & Turnshek 1991), and N_* is adjusted to maintain equal total lines in the model and triplet sample (for $1.99 < z < 2.49$). (The measured number lands within 10% of predictions from the literature, after adjusting for different sample sensitivities.) We ignore momentarily the possibility that the proximity effect is modified by large scale structure influencing the local number density of Ly α lines (Loeb & Eisenstein 1995).

To illustrate the correlation of observed $n(z)$ with predicted deficits of lines due to the proximity effect, we present Figure 8, which shows the general evolution of $n_\gamma(z)$ (dotted line) absent the effects of local radiation, the altered $n_p(z)$ (solid curve) predicted by the proximity model of Bajtlik et al. (1988) assuming $J_{21} = 1$, and the actually observed density of lines n_o in redshift bins selected to be equally spaced in redshift but well-placed with respect to foreground QSOs (crosses showing z intervals and 1σ error bars in n_o). Figure 9 shows the same information for LB 9612, which has LB 9605 in the foreground, as well

as a minor contribution from the $V = 18.2$, $z = 1.818$ LB 9615 sitting $9 h^{-1}$ Mpc to one side. Note that there is some correlation with the model n in the LB pair, but in most cases the counts and model are *anti-correlated* for the triplet. The signal involved is still small compared to the errors, so we weight the data in a more optimal way, first explained in Crotts (1989), and repeated below.

The weighting factor, applied to each line observed in the redshift interval with significant $n_\gamma - n_p$, is just the line density deficit $w = 1 - n_p/n_\gamma$ at that redshift (*not* ω from Bajtlik et al. [1988]). The sum over observed lines is compared to predictions from the two models: w integrated over $n_\gamma(z)$, and w integrated over $n_p(z)$. Lines are only considered and integrals only calculated over regions where $w > 0.1$. The results are shown in Table 7.

As in Crotts (1989), the observed signal is consistent with the no-proximity model, and lends no support to the model including foreground ionization, being discrepant with that model at the 2.4σ level. This result persists despite the new spectroscopy, inclusion of lines with $0.1\text{\AA} < W_o < 0.2\text{\AA}$, and the addition of LB 9612. Two other papers, Dobrzycki & Bechtold (1991) and Fernández-Soto et al. (1995) bear on the foreground-QSO proximity effect. The latter detects a marginally significant signal consistent with a foreground effect, while the phenomenon seen by Dobrzycki & Bechtold is much too strong to be explained by a simple interpretation of QSO ionization effects for the brightness seen for the foreground QSO. As Loeb & Eisenstein (1995) point out, the proximity effect in the case of a single QSO can be altered by the effects of large scale structure in the immediate vicinity of the QSO, in the sense that cluster produces more Ly α lines near the QSO’s Ly α emission. This effect is strongest for faint QSOs, where ionization is weak.

Even though the QSOs studied here tend to be faint because of the requirement that they reside in close pairs, the Loeb & Eisenstein result does not explain why these might be so discrepant with the Bajtlik et al. model while bright QSOs are not. Furthermore, we

have chosen a value of J_{21} that is often regarded as low. One should recall that anisotropic radiation by the QSO or long term variability on timescales of about 10^5 y (Crotts 1989) are potential means by which the foreground QSO proximity effect can produce a signal that is out of proportion with the observed flux, while the direct (single QSO) proximity effect involves Ly α clouds along the observed sightline to the ionizing source and photons emitted at the same time as the ionizing photons. If these factors are manifest here, a much larger sample will be needed to reveal them. The current sample does not lend additional support to the ionization interpretation of the proximity effect by way of the foreground QSO test.

4.4. Ly α Absorber Size Estimates

The power of QSO pairs in providing transverse information is crucial to finding the size of absorption clouds, particularly in the forest. We (Papers II and III) have constructed a simple statistical measure of cloud size based on the working assumption that Ly α are unclustered spheres of uniform radius. In Paper III, however, we show that this assumption cannot be completely accurate because the inferred cloud radius R is a function of the QSO pair separation S , contrary to the basic assumption. Much of this failure is based on the behavior of absorbers in the KP QSO triplet, which we re-examine here. Furthermore, Dinshaw et al. 1995 also consider the pair Q0107-0234/0107-0235, which is of much lower redshift than the other pairs that have been studied, and suggest that the cloud size increases with lower z . The LB pair allows us to test this possibility.

Our technique consists of an analysis of “hit” statistics, a hit consisting of a line above a set W_o threshold detected in both sightlines of a QSO pair, with a velocity difference between the two absorption line redshifts less than a velocity difference cutoff. Figure 4 of Paper III shows that a cutoff of $\Delta v = 150 - 200$ km s $^{-1}$ is strongly suggested by the

the presence of a strong cross-correlational signal between all published sightlines up to the scale of the KP triplet’s separations, and is further borne out in §4.3 by the clustering feature at $\Delta v < 200 \text{ km s}^{-1}$ seen in the triplet.

When a line is seen in one QSO spectrum, but no line above the W_o threshold is seen within 200 km s^{-1} in the other (and this can be established with greater than 3.5σ certainty) it is registered as a “miss.” (If such a situation is not established with 3.5σ certainty, it is “null.”) We assume in turn one of three cosmological models: $(\Omega_0, \Lambda_0 = \Lambda/3H^2) = (1, 0)$, $(0.1, 0)$ and $(0.1, 0.9)$. In all three cases, for the relevant ranges of redshifts, we can consider the separation between sightlines to be nearly constant, with an order-unity ratio between sightline separations (listed in Fang et al. 1996 for all QSO pairs considered here except the LB pair) for the three cosmological cases. For the LB pair. multiply the (1,0) value by 1.38 for (0.1,0) and 1.9 for (0.1, 0.9).

We limit our sample to lines with $W_o \geq 0.4\text{\AA}$ for all QSOs, and include the “contaminated” Ly α lines for the triplet and LB pair. In Table 8, we show the Ly α forest redshift ranges, angular separations, proper separation range for (1, 0), hit and miss counts, inferred 95% confidence intervals, and median predicted cloud radii ($q_o = 1/2$) for the QSO pairs Q1343+2640 (Papers II and III), Q0307-1931/0307-1932 (Shaver & Robertson 1983), Q0107-0234/0107-0235 (Dinshaw et al. 1995), and new values for Q1623+2651A/1623+2653/1623+2651B, Q1517+2357/1517+2356 and Q1026-0045A/B. (See note added in proof.)

[Note added in proof: Q1026-0045A/B (Petitjean et al. 1998), like Q1517+2357/1517+2356 are two low-redshift QSOs in a close pair observed by the FOS on *HST* using the G270H grating. These data are now included in Table 8, Figure 10 and the results of this section. We have reanalyzed the linelist and spectra of this pair, imposing the same $W_0 = 0.4\text{\AA}$ cutoff as for the other pairs, which coincidentally results in

a somewhat smaller R value than do the W_0 cutoffs used by Petitjean et al. Nonetheless, adopting their values does not change the results of this section significantly.]

The estimates for the KP triplet were computed by taking each pair of QSOs separately; strictly speaking they are not quite independent. Also, for these samples there are significant numbers of accidental hits; these are corrected as follows: we assume a Poisson distribution for the number of random hits, with the mean of $N_{rand} = 11.6/3 = 3.87$ random hits per QSO pair. The number of “real” (non-random) hits, N_{real} are given by the observed number minus the random component. Since the real component must be non-negative, that part of the distribution with N_{rand} greater than N_h is included in the $N_{real} = 0$ bin. Each $N_{real} > 0$ produces its own probability density distribution in $\mathcal{P}(R)$ (as in Paper III) while cases where $N_{real} \leq 0$ produce only an upper limit in R . (The probability distributions for cases where $N_{real} \leq 0$ are taken as constant in R : $\mathcal{P}(R) = \begin{cases} 0, & R < S/2 \\ \text{constant}, & R \geq S/2 \end{cases}$. Fortunately, these cases are a small fraction of the total.) The median R value and corresponding R confidence intervals are computed by taking an average of the probability distributions corresponding to a different N_{real} , weighted by this truncated Poisson distribution. The results are slightly smaller in median R , and with smaller errors, than those derived from Crofts (1989) data in Paper III.

The LB pair is particularly interesting because it lands mid-range in the span of S values from pre-existing pair observations, but is at significantly lower redshift than average. Unlike the lower redshift pair Q0107-0234/0107-0235 (Dinshaw et al. 1995), however, it does not imply R values significantly higher for pairs at lower redshift.

Figure 10 shows the median R and confidence intervals in R (corresponding to $\pm 1\sigma$) for all QSO pairs, as a function of S . As discovered in Paper III, there is a significant trend of median estimated R with S , contrary to our assumed model. The slope in a linear fit of R versus S is 0.43 ± 0.08 for all QSO pairs. If, noting that Q0107-0234/0107-0235

appears to be discrepant, one leaves it out, one finds that the trend of R with S is almost unchanged and more significant, with slope of 0.43 ± 0.08 . The other lower redshift QSO pair, Q1517+2357/1517+2356, falls *below* the trend set by higher redshift QSOs (as does Q1026-0045A/B).

With the $R(S)$ dependence removed, one finds the Q0107-0234/0107-0235 point sitting 2.3σ above the minimum χ^2 linear fit of R versus z , with Q1517+2357/1517+2356 0.9σ below, and Q1026-0045A/B 0.8σ below. There is no significant trend of size increase with z (best fit $\partial R/\partial z = 21$ kpc per unit z , with an error of 51 kpc per unit z). While Q0107-0234/0107-0235 suggests a trend of R with z , this trend is not supported by any other data, and Q0107-0234/0107-0235 alone is insufficient to establish an effect. Perhaps $R(z)$ changes more rapidly at smaller z than at larger, but more data from close, low redshift QSO pairs would be needed to substantiate this.

Paper III shows that there are at least three viable alternatives for the dependence of R on S : small scale clustering, elongated clouds (filaments) and a non-uniform R value among the clouds. From QSO pairs alone, it is very difficult to distinguish which of these, or which combination, is in play. The triplet data, however, is used below to probe the shape of Ly α forest clouds.

4.5. Elongated Absorbers

It is also possible to use “hit” statistics to test directly the non-spherical models. For instance, we can ask if Ly α absorbers are elongated, by simulating the projection of a simple shape against the sky in an isotropic collection of orientations. Paper III suggests elongation of the clouds into filaments as one of several possible explanations for a dependence of inferred cloud size R from our Bayesian model on sightline separation S .

Furthermore, numerical models of intergalactic objects in the early Universe (Zhang et al. 1995, Katz et al. 1995, Miralda-Escudé et al. 1996) tend to find elongated structures on the scale of several hundred kpc as those with properties most similar to Ly α clouds. This should be contrasted to purely gravitational simulations e.g. Shandarin et al. (1995), which tend to produce sheet-like structures first. The triplet is ideal for determining whether the hit statistics deviate from an S -independent R due primarily to elongated clouds; single, long, thin filaments are incapable of intercepting all three sightlines. QSO triplets carry with them the potential to measure the aspect ratio of filaments, $a = l/2R$, and R independently (where R is the cross-sectional radius, and l is the length of the filament).

One possibility that we do not discuss in this subsection are sheets or disks ($a < 1$), since their behavior in terms of hit statistics is similar to spheres of slightly smaller radius (Paper III) in the case of sightline pairs. This is still true for triple sightline hits. As $a \rightarrow 0$, the utility of the triple sightline approach is to distinguish the face-on projected shape of the disk, which we judge to be a less interesting problem. We discuss other test for disk-like structure in §4.7 and 4.8. Here we pursue the following question: are the two- and three-way hit statistics in the QSO triplet consistent with elongated, circular-cross-sectioned rods of some radius R and aspect ratio a ? This is motivated by the realization that long, thin filaments cannot span all three sightlines (if the minimum distance across their triangle projected onto the sky is larger than the width of the filament), whereas a circular cloud of the same volume as the filament might easily do so. Such an effect should be expressible as the probability of clouds of a given shape and size hitting two or all three sightlines whenever they hit one. This is accomplished by, first, measuring in the actual spectra’s linelists the probabilities P_{ab} , P_{ac} , P_{bc} and P_{abc} , (defined as P_{ab} being the probability of a line in A resulting in a hit in B, or vice versa, and likewise for the other probabilities) and, secondly, simulating the same probabilities by a numerical simulation of cylindrical rods of various a and R values oriented in an isotropic distribution and intercepting (or not) two or

three sightlines with the same spacings as those between KP 76, 77 and 78 (sightlines “A”, “B” and “C”, respectively).

For this test, we need the largest sample possible, hence for $W_o > 0.4\text{\AA}$, the $\langle z \rangle = 2.14$ sample. As a preliminary indication, consider that of the 29 $W_o > 0.4\text{\AA}$ hits, some 15.6 are expected at random. Consider also the large number of “multiple hits” of two or three pairs between all three sightlines involving the same Ly α clouds, at $z = 1.938$ (three pairs involving three lines in all three QSO spectra), $z = 2.042$ (three pairs, three lines, three QSOs), $z = 2.113$ (three lines, two pairs, three QSOs), $z = 2.138$ (three lines, three pairs, three QSOs) and $z = 2.183$ (three lines, three pairs, three QSOs), for a total of fourteen pairs. In other words, the entire excess in $\Delta v < 200 \text{ km s}^{-1}$, $W_o > 0.4\text{\AA}$ pairs might be due to these five groupings. This, even by itself, argues for clouds that are not simply long, thin filaments (in comparison to the sightline separations), since such clouds cannot span the three sightlines.

The probabilities P_{ab} , P_{ac} and P_{bc} are computed by counting the number of relevant pairs and dividing by the geometric mean of the number of lines in each sightline’s sample that is involved (23, 24 and 29 in KP 76, 77 and 78, respectively, for $W_o > 0.4\text{\AA}$), eliminating the fraction of pairs that are expected at random (reduced to a fraction of $13.4/29$ of the original). Errors are computed from the Poisson distribution around a mean equaling the actual number of observed hits. For three-way hits (P_{abc}), since any given line has a 35% chance of being accidentally involved in a hit, the probability is reduced by this fraction. Errors are computed to first order by considering the Poisson statistics for the multiple hits (since they are likely not chance events) and in the sample size, then adding in quadrature the error in false hits, leading to the 68% confidence interval (corresponding to $\pm 1\sigma$) assigned to each probability: $P_{ab} = 0.30^{+0.19}_{-0.15}$, $P_{ac} = 0.18^{+0.16}_{-0.12}$, $P_{bc} = 0.06^{+0.14}_{-0.10}$, and $P_{abc} = 0.16^{+0.14}_{-0.10}$. Formally, P_{bc} cannot be less than zero, nor smaller

than P_{abc} ; its small value appears to be a result of an unusually small number of random hits in BC. If we compute the probabilities in a different way, by recognizing that triple hits are almost certainly real (not accidental) and that the remaining number of real hits must be non-negative, this produces a new set of probabilities for the pairs of sightlines: $P'_{ab} = 0.24^{+0.20}_{-0.13}$, $P'_{ac} = 0.12^{+0.13}_{-0.12}$, and $P'_{bc} = 0.15^{+0.13}_{-0.11}$. Normally (if the clouds are oriented isotropically and parcels of gas within the cloud have a two-point correlation function that decreases monotonically with separation), one should expect $P'_{ac} \geq P'_{ab} \geq P'_{bc}$. The probability P'_{ac} disobeys this most significantly; we will encounter this again below.

As a comparison, we produce a model of a single, rotating, translating cylinder (of circular cross-section) that is stepped in a fine grid ($10 h^{-1}$ kpc in two orthogonal directions perpendicular to the sightline) across three sightlines with the same spacing as the triplet. The rod is “hard-edged” with no variation in W_o over its projected shape. The rod is made to point in 1280 isotropically distributed directions at each grid point. This simulation is done for rods with cross-sectional radii R that are positive multiples of $25 h^{-1}$ kpc up to $500 h^{-1}$ kpc (in proper coordinates), and for aspect ratios (length divided by diameter) of positive integral values up to 20. For each rod shape, size, orientation and translation, the hit on one, two or three sightlines, A, B, C, AB, AC, BC or ABC, is evaluated. For each translational grid, the number of one-way hits are required to be all equal, $N_a = N_b = N_c$. The probabilities are computed for each rod shape and size by $P_{ab} = N_{ab}/N_a$, ... , $P_{abc} = N_{abc}/N_a$. Example contour plots (unsmoothed) of two of these probabilities, P_{ab} and P_{abc} , respectively, are shown in Figures 11a and 11b. P_{ac} and P_{bc} resemble P_{ab} , qualitatively, while P_{abc} , containing information about the shape, is more distinct, going to zero for $2R < 406 h^{-1}$ kpc, the minimum distance across the triangle described by the triplet. The contours at $P = 0.01$ show a few ripples at the level of about 0.002, indicating the degree of discreteness error in the model.

The contours for the calculated value for each probability P_{ab} , etc. (solid curves) and a confidence interval (68% - dotted curves) is plotted in Figure 12a. The same for P'_{ab} , etc. is plotted in Figure 12b. The probability P_{abc} is inconsistent with the mean of the two-way probabilities P_{ab}, P_{ac}, P_{bc} at a level greater than 1σ for any aspect ratio $a > 4$ (accounting for the errors in all P). For $a \lesssim 2$, in both plots, P_{abc} is consistent with P_{ab} and P_{bc} (or P'_{ab} and P'_{bc}) at a level less than 1σ . For P_{ac} (or P'_{ac}), however, the disagreement with P_{abc} is of the order of $1 - 2\sigma$ even for $a \lesssim 2$. As noted above, P_{ac} is anomalously low relative to the other probabilities, and this is reflected here. Also, the statistical significance of the difference between large and small a is not great, decreasing from a maximum 1.2σ for large a to $0.6-0.7\sigma$ for $a < 2$. Nevertheless, all probabilities have best agreement for $1 < a < 3$ and $198 h^{-1}\text{kpc} < R < 510 h^{-1}\text{kpc}$ (larger R at smaller a), where $\sigma < 0.8$ (weighting the three two-way probabilities at two-thirds that of P_{abc}).

The result that the longest dimension across these absorbers exceeds somewhat $700 h^{-1}\text{kpc}$ is guaranteed by the observation that there are significant numbers of hits between the sightlines, plus the assumptions of the model. The derived shape and size must span the sightlines; however, the way in which it does so - by long, thin clouds or large near-spheres - depends on the relative number of three-way hits. We conclude that unclustered filaments alone are less likely to explain our shape information on the $W_o > 0.4\text{\AA}$ Ly α forest. The absorbers are more likely to be nearly circular in cross-section (disks or spheroids), or, if elongated, their hit behavior on the scale of hundreds of kiloparsecs must be dominated by clustering of filaments, not the shape of the filaments themselves.

Obviously, given Figure 6, no such $\Delta v \leq 200 \text{ km s}^{-1}$ triple hits exist for the $W_o > 0.8\text{\AA}$ sample. Expanding the velocity interval corresponding to a hit to 600 km s^{-1} , the interval of possible $W_o > 0.8\text{\AA}$ clustering seen in Figure 6, we find one triple hit ($z = 2.05665$, $W_o = 0.86\text{\AA}$ in KP76; $z = 2.05506$, $W_o = 1.24\text{\AA}$ and $z = 2.05056$, $W_o = 1.77\text{\AA}$ in KP77;

$z = 2.06117\text{\AA}$ in KP78), being composed of four lines, not just three. This feature is completely independent of the $\Delta v \leq 200 \text{ km s}^{-1}$, $W_o > 0.4\text{\AA}$ triple hits above, and contributes one hit to the P_{ab} , $W_o > 0.4\text{\AA}$ signal. It is spread over 1040 km s^{-1} ; this is about six times the Hubble flow across the transverse dimension of the QSO triplet. We should note, however, that we would expect approximately 2.1 such triple hits at random in this sample, so there is little to be concluded from this datum.

Likewise, even though there is a statistically insignificant excess in two-way hits in the $0.2 < W_o \leq 0.4\text{\AA}$ sample; this might mask a more significant three-way signal. In truth, there is a slight deficit in such three-way hits compared to the random expectation, so we can conclude little, except that P_{abc} is likely smaller for $0.2 < W_o \leq 0.4\text{\AA}$ than for the $W_o > 0.4\text{\AA}$ sample.

4.6. Consistency of Triplet Hits with Spherical Absorbers

Are spheres of different R required to explain P_{ab} , P_{ac} , P_{bc} and P_{abc} ? Or is a distribution of spheres of different radii even consistent with the data? Figure 13 shows how the four probabilities vary for a given uniform R value common to the whole population of spherical clouds. A single R value should be consistent with the 95% upper limits on all three P' values and P_{abc} . This implies an upper limit $R < 468 h^{-1} \text{ kpc}$ from P'_{ac} . On the other hand, all of the two-way probabilities (P_{ab} , P_{ac} , P_{bc} , P'_{ab} , P'_{ac} , P'_{bc}) are roughly equal, a condition of large ($R > 600 h^{-1} \text{ kpc}$) clouds. For such large clouds, however, P values are much larger ($\gtrsim 0.3$). In order for both the ratio in P values and their rough magnitudes to be satisfied by a distribution of spheres of varying radii, a sub-population of $R > 600 h^{-1} \text{ kpc}$ clouds must be diluted by a larger portion ($\sim 50\text{-}70\%$ of the total cross-section) of smaller clouds which do not span the sightlines and hence do not contribute significantly to hit counts. These reduce all P values by the proportion between the cloud sub-populations' total

cross-section, but keep the ratios of various P values intact at their $R > 600 h^{-1}$ kpc ratios. Such a spectrum of cloud sizes is consistent with our previous constraints (Paper III) on a power-law distribution of spherical cloud radii, which we do not re-derive here. We have not yet managed to challenge this hypothesis on the basis of measured cloud parameters.

4.7. Kinematics of Flattened Absorbers in the Hubble Flow

While it is difficult with hit statistics to distinguish disks from spheres, we can use the Hubble expansion to probe the probable shape of a cloud. Starting as an object expanding nearly as fast as the rest of the Universe, the absorber may collapse in one or two dimensions while still expanding in an orthogonal one. We can then distinguish a filamentary or sheet-like object by the tilt of the direction of expansion relative to the line of sight, with one side expanding toward the observer, while the other recedes.

The three sightlines of the triplet rest on a circle 189.7 arcsec in diameter, separated in the sky by 90° , 110° , and 160° with respect to the center, close enough to equilateral to always sense most of the velocity shear across the circle for an expanding sheet. For the five triple-hit objects, we find the best fit in magnitude and angle of the line of nodes for this shear pattern, and find maximum velocities across the circle’s radius of 20, 35, 175, 65 and 95 km s^{-1} (to the nearest 5 km s^{-1}) for the $z = 1.938, 2.043, 2.113, 2.138$ and 2.183 objects respectively.

In comparison the Hubble expansion across this radius at $z \approx 2.1$ is about 165 km s^{-1} (to within about 20% for the cosmological models we consider), whereas various inclination angles i can project this to zero or nearly infinite velocities. Figure 14 shows the expected cumulative distribution of shear velocities for a sheet expanding in the Hubble flow, for a random distribution of i values, and for our three cosmological models. A mean

measurement uncertainty of 20 km s^{-1} is folded into the v_{max} distribution.

Figure 14 allows us to use a one-sample Kolmogorov-Smirnov (K-S) test to determine whether the observed v_{max} distribution is consistent with theoretical expectation. For the three cosmological models, (1, 0), (0.1, 0) and (0.1, 0.9), respectively, the null hypothesis (consistency with Hubble expansion within sheets or disks), cannot be rejected, at levels of 50%, 70% and 99%, in the sense that (0.1, 0.9) is more consistent. The K-S test does not reject a model based on expanding sheets, while elongated filaments encounter difficulty in §4.5. Likewise, we cannot reject a simple gaussian distribution of velocities. We need a few times as many such measurements to discriminate between these two models.

A further prediction of the sheet model is a correlation between v_{max} and W_o , which might be evident unless the perpendicular column density through different absorbers or along different sightlines in the same cloud shows scatter greater than about order unity. Such a correlation should be a proportionality, or at least monotonic, hence susceptible to a rank-order test. We choose the median W_o value of all lines contributing to the triple hit objects. The results from Spearman’s Rank Correlation test shows that the $W_o > 0.4\text{\AA}$ sample is consistent with a monotonic $v_{max}(W_o)$ at the 72% confidence level. When the $W_o > 0.8\text{\AA}$ triple hit is included, however, the confident level becomes 93%, suggestive of the tilt of the absorber being an important parameter. We should note that when the same test is applied to two-way hits, however, no such correlation is seen. This may suggest that three-way hits must be required to bring this correlation out of the noise, or that the objects which span the three sightlines are sheet-like.

4.8. Other Tests of Ly α Absorber Shape, Size and Clustering

In the Introduction we review the several recent theoretical works proposing observational tests involving pairs of sightlines. Most of these can be applied to the current data, and we consider them in turn.

Many of these tests involve figures published in the four theoretical works. While we present our data here in a form which can be compared most directly to these other results, we avoid reproducing all of their relevant figures, and refer the reader to the original papers (Cen & Simcoe 1997, Charlton et al. 1995, 1997, Miralda-Escudé et al. 1996). Additionally, Charlton et al. (1997) discuss other kinematical tests similar to those considered in the previous sections, which we will not rediscuss here.

4.8.1. Correlated Flux between Sightlines (Miralda-Escudé et al. 1996)

Miralda-Escudé et al. (1996) consider the correlation of Ly α absorption as a function of transverse separation between adjacent sightlines. This is expressed purely in terms of the correlation of the transmitted flux between sightlines, not correlated line detections as in this paper. They define a correlation coefficient $\xi_f(\Delta v, \Delta r)$ (*not* a two-point correlation function as usually defined) which describes the correlation between the transmitted flux F in two adjacent sightlines:

$$\xi_f(\Delta v, \Delta r) = \langle [F(r, v_0) - \langle F(r, v) \rangle_v] [F(r + \Delta r, v_0 + \Delta v) - \langle F(r + \Delta r, v) \rangle_v] \rangle_r / \{ \langle F^2 \rangle_{v,r} - \langle F \rangle_{v,r}^2 \},$$

where for instance, $\langle F(r, v) \rangle_v$ refers to the expectation value of F along a sightline at location r on the sky, averaging over the sightline (which is parameterized by velocity v along the sightline. Note that Δr corresponds to our S .) Necessarily, $-1 < \xi_f < 1$ and $\xi_f \rightarrow 1$ for $\Delta v \rightarrow 0$ and $\Delta r \rightarrow 0$. They show (in their Figure 13) that $\xi_f(\Delta v, \Delta r)$ drops to about 0.5 of its peak ($\Delta v = 0$) value at $\Delta v \approx 60 - 120 \text{ km s}^{-1}$ for various Δr , and

drops close to zero for $\Delta v \gtrsim 250 \text{ km s}^{-1}$ (less than 0.1 for $\Delta v \gtrsim 130 \text{ km s}^{-1}$), regardless of Δr . The peak at $\Delta v = 0$ falls to 0.5 at $100 h^{-1} \text{ kpc}$ (proper separation) and to 0.17 at the largest Δr shown, $418 h^{-1} \text{ kpc}$. While this prediction does not quite extend to Δr values for the KP triplet, 496 to $720 h^{-1} \text{ kpc}$, it is reasonably securely extrapolated to $\xi_f \approx 0.06$ at $\Delta r = 599 h^{-1} \text{ kpc}$, the mean for the triplet. All of these values apply at $z = 3$.

Since we do not resolve most of the Ly α forest, we cannot compute ξ_f directly. We take this opportunity to note that analysis of theoretical models of the high redshift neutral hydrogen distribution should continue to consider the alternative approach of correlated line detections. Here and in many potential cases in the future, QSOs in close pairs are sufficiently faint that lines can be detected but not usefully resolved, even with 8-10 meter class telescopes. Nevertheless, we can compute the statistical moments of F e.g. $\langle F(r, v) \rangle_v$ and $\langle F^2(r, v) \rangle_v$ since we also have high resolution Keck HIRES data for KP 77 (Crofts et al. Tytler 1997), finding $\langle F \rangle_v = 0.725$ and $\langle F^2 \rangle_v = 0.807$. (Note that we cannot take the expectation over r , of course.) For the $W_0 \geq 0.4 \text{ \AA}$ lines in this sample, not all covered by the HIRES data, we attempt to translate our data on absorption lines into measures of the correlation of actual flux, treating Ly α forest spectra as continuous functions in wavelength rather than discrete lines. This is accomplished by considering only the lines with $W_0 \geq 0.4 \text{ \AA}$, since the rest are uncorrelated. These lines are replaced with Voigt profiles of the same W_0 and an assumed value of the Doppler parameter $b = 30 \text{ km s}^{-1}$. (The result is fairly insensitive to the adopted b value.) This results in the value measured from our $\langle z \rangle = 2.14$, $W_0 \geq 0.4 \text{ \AA}$ KP sample of $\xi_f(\Delta v = 0, \Delta r = 599 h^{-1} \text{ kpc}) = 0.069$, with 1σ errors of about 0.01. This value is consistent with the theoretical $\xi_f \approx 0.06$.

When we attempt the same calculation for the close pair 1343+2640A/B at $\langle z \rangle = 1.86$, we find $\xi_f(\Delta v = 0, \Delta r = 40 h^{-1} \text{ kpc}) \approx 0.40$, with 1σ errors of about 0.05. This should be compared to a model prediction of about 0.8. This difference is due in part to the fact that

we have ignored weaker lines, but even in 1343+2640A/B these are more weakly correlated, as we consider in the Discussion section. Most likely the measured value remains smaller than predicted, most likely $\xi_f(\Delta v = 0, \Delta r = 40 \ h^{-1}\text{kpc}) \lesssim 0.6$.

4.8.2. Fraction of Coincident Lines versus Δr and Δv (Cen & Simcoe 1997)

Cen and Simcoe (1997) use the same simulation as Miralda-Escudé et al. (1996) to study the nature of individual clouds of H I, over redshifts $2 < z < 4$. They study clouds as defined by regions isolated by different threshold baryonic density cuts expressed in terms of mean baryonic density $\rho(x)/\langle\rho\rangle > \rho_{cut} = 3, 10$ or 30 , values chosen by the authors. They find clouds that are relatively round and small (mean radii $\approx 23 \ h^{-1} \text{ kpc}$ for $\rho_{cut} = 10$ and $33 \ h^{-1} \text{ kpc}$ for $\rho_{cut} = 30$, and commonly with axis ratios of about 1:2:4 or, a smaller fraction of the time, closer to spherical). They also argue that on scales larger than these mean diameters any observed hits in adjacent sightlines are due to clustering of clouds, not cloud structure itself. Nevertheless, it is clear from the contours at lower ρ that larger, more sheet-like or filamentary chains of clouds are also present in the simulation, on scales up to nearly the simulation box size of $2.5 \ h^{-1} \text{ Mpc}$ (proper) at $z = 3$. For comparison with observations, they state that $\rho_{cut} = 10$ in their simulation corresponds to $N_{HI} = 1.1 \times 10^{14} \text{ cm}^{-2}$, or $W_o = 0.29 \text{ Å}$ for $b = 30 \text{ km s}^{-1}$, which together with the corresponding value for $\rho_{cut} = 30$, $W_o = 0.47 \text{ Å}$, straddles our limit $W_o = 0.4 \text{ Å}$.

In close analogy to our Figure 10 and Table 8, Cen & Simcoe present their Figure 9, which describes the fraction (compared to all lines) of lines coincident between QSO sightlines as a function of proper transverse separation Δr and velocity “hit” window width Δv . We find that the line correspondence ratio (corresponding to their Figure 9’s ordinate) is $N_{co}/N_{tot} = 0.93 \pm 0.06, 0.29 \pm 0.17, 0.40 \pm 0.11, 0.57 \pm 0.13, 0.18 \pm 0.06, 0.38 \pm 0.07, 0.27 \pm 0.07$ and 0.22 ± 0.06 , respectively, for the pairs listed in Table 8, in order of increasing separation,

with r.m.s. binomial error shown. This is computed considering that a hit corresponds to two lines in the sample. A comparison with the $\Delta v = 150 \text{ km s}^{-1}$, $\rho_{cut} = 10$ or 30 curves from Cen & Simcoe Figure 9 shows that all pairs, with the possible exception of Q1026-0045A/B and the LB pair (with $N_{co}/N_{tot} = 0.18$ at $\Delta r = 432 \text{ } h^{-1} \text{ kpc}$, which falls off of the graph in Δr), lie at least one sigma above the highest corresponding theoretical curve. (The KP points are also off of the graph, but seem to lie at least one sigma above, as well.) While we use $\Delta v = 200 \text{ km s}^{-1}$ in Table 8, the effect of this over $\Delta v = 150 \text{ km s}^{-1}$ is small compared to the difference between theoretical and measured results. Furthermore, Cen & Simcoe’s Figure 9 applies to $z = 3$, but their Figure 10 shows that N_{co}/N_{tot} does not grow at all between $z = 3$ at the typical redshifts $z \approx 2$ of the sample in Table 8. The simulated absorption lines are less correlated between sightlines than the observed ones.

This general result for N_{co}/N_{tot} is consistent with the small $\xi_f(\Delta v = 0, \Delta r = 40 \text{ } h^{-1} \text{ kpc})$ result of Miralda-Escudé et al. (1996), which is not surprising given their use of the same model. Casting this in terms of the small clouds delineated by Cen & Simcoe, one tends to conclude that more power is needed in their model on wavelengths of $\sim 100 - 1000 \text{ } h^{-1} \text{ kpc}$, which is slightly smaller than the proper size of the simulation volume of $2.5 \text{ } h^{-1} \text{ Mpc}$ at $z = 3$.

4.8.3. *Spatial Clustering of Ly α Absorbers (Cen & Simcoe 1997)*

Cen & Simcoe plot the cloud two-point correlation function $\xi(r)$, where r is the comoving separation between absorbers, in their Figure 14. Our measurement of clustering in the KP triplet at separations $\langle S \rangle = 599 \text{ } h^{-1} \text{ kpc}$, plus a line-of-sight component $\Delta v = 200 \text{ km s}^{-1}$ yields a typical proper separation of $625 \text{ } h^{-1} \text{ kpc}$. At $z = 3$ this produces $\xi = 0.19$ and 0.27 , for $\rho_{cut} = 10$ and 30 , respectively. Our measurement of ξ was made at a different redshift $\langle z \rangle = 2.14$, but Cen & Simcoe’s Figure 15 allows us to account for

the evolution of clustering power from $z = 3$ to 2.14, between which correlation length r_0 increases by about 10%. Given a correlation function $\xi \propto r^{-1.8}$, the value of ξ at a proper separation of $625 h^{-1}$ kpc should increase by about 18%. Since we measure a value at this separation of $\xi = 1.88^{+0.78}_{-0.50}$, we find that the $\rho_{cut} = 30$ model result and actual measurement are inconsistent at about the 3σ level. This may also be due to the lack of longer wavelength modes in the clustering power spectrum, as Cen & Simcoe also speculated.

4.8.4. Fraction of Coincident Lines versus Δr and Δv (Charlton et al. 1997)

Like Cen & Simcoe, Charlton et al. (1997) consider model simulations (Zhang et al. 1995) to construct statistical measures which can be compared to observations. Also like Cen & Simcoe, they discuss how the fraction of common lines varies with sightline separation S (their D). Their Figure 2e corresponds most closely to our sample, with $z = 2$ and a curve at $N_{HI} = 10^{14} \text{cm}^{-2}$. This value of N_{HI} is slightly smaller than our $W_0 = 0.4 \text{\AA}$ cutoff for typical b values. The values of N_{co}/N_{tot} (their f_{co}) listed above for $z \approx 2$ samples (excluding 0.57 for 0107-0234/35) all scatter within 1σ of the theoretical curve, except for 1517+2356/57, which is too low, and the adjacent value, 1623+2651A/B, which is too high. All six QSO pairs, taken together, are consistent with this curve and have residuals that are might arise from a reasonable χ^2 distribution.

4.8.5. Median Absorber Size Implied from Hit Statistics (Charlton et al. 1997)

Charlton et al. (1997) study how the size of clouds implied by hit statistics change with pair separation, for the structures within the numerical model (Zhang et al. 1995). This implied size depends on whether one assumes as a working model for the clouds a shape of spheres or thin disks. Figure 3 of Charlton et al. (1997) corresponds closely to our Figure

10. Unfortunately, none of their sub-figures correspond exactly, but their Figure 3f is a close match, using $\Delta v = 150 \text{ km s}^{-1}$ instead of 200 km s^{-1} , and disks instead of spheres. From Paper III, however, results for spheres can be converted to disks by multiplying by a factor of about 1.5. With this adjustment, all $z \approx 2$ pairs fall within about 1σ of the theoretical curve, with the small S curve slightly undercutting the observed values.

4.8.6. *Linestrength Correlation between Sightlines (Charlton et al. 1995, 1997)*

In Charlton et al. (1995) a co-distribution of column densities (N_a and N_b) for adjacent sightlines a and b of various separations is considered for various idealized disk-shape cloud models, whereas in Charlton et al. (1997) the same test is applied to the model simulation of Zhang et al. (1995). In the first case, they consider separations up to the cloud diameter, with the best discrimination occurring for separation less than about the cloud radius. In the second paper, they consider proper separations up to $200 h^{-1} \text{ kpc}$. Given the separation range of the theoretical effect, 1343+2640A/B and 0307-1931/32 are most valuable comparison among observed pairs. We will also consider the KP triplet. Following Paper III, it is wise to consider only those lines thought to be unlikely to be contaminated by interloping metal lines, and with a $S/N = 3.5$ cutoff imposed.

Again, our data are expressed in terms of W_0 , not N_{HI} , so we must assume a value for b (of 30 km s^{-1}), which will introduce scatter into the transformation between W_0 and N_{HI} . Fortunately, Charlton et al. (1997) also recompute the effect in terms of the difference of equivalent widths $|W_a - W_b|$ versus the strength of the strongest line $\max(W_a, W_b)$ (their Figure 5) which is directly comparable to Figure 2b of Paper III (except for the two distributions corresponding to slightly different S values, $40 h^{-1} \text{ kpc}$ for the observed pair 1343+2640A/B and $50 h^{-1} \text{ kpc}$ for model). The tight theoretical correlation is supported by the observed values, with none of the observed W_0 locii for uncontaminated lines being

inconsistent with the theoretical result, and with the potentially contaminated lines also being in reasonable agreement. As Charlton et al. (1997) note, a larger data set would be desirable.

We also consider the pair 0307-1931/32 at $S = 231 \ h^{-1}$ kpc separation. Figure 15a shows the distribution of $|W_a - W_b|$ versus $\max(W_a, W_b)$ for 0307-1931/32, analogous to Figure 2b of Paper III for 1343+2640A/B. (Since we could not reanalyze this spectrum, we do not attempt to remove Ly α potentially contaminated by superimposed metal lines.) In general, the points in Figure 15a must lie below the $|W_a - W_b| = \max(W_a, W_b)$ diagonal, and the farther they fall from this line, the more homogeneous they are. Unlike the idealized models of Charlton et al. (1995), with analogous results presented in their Figure 1, there is still a close agreement between the observed wide-pair locus and the locus predicted for very close pairs e.g. Charlton et al. (1997) Figure 5. We draw no interesting conclusion from this comparison.

The results for $|W_a - W_b|$ versus $\max(W_a, W_b)$ are more interesting for the KP triplet, as shown in Figure 15b. Due to the density of points, we do not present error bars, which are typically much less than 0.1\AA (hence about the size of the point symbols). Each point represents a Ly α forest line coincidence ($\Delta v < 200 \text{ km s}^{-1}$) free of probable metal-line contamination (from systems at different redshifts) and without associated metal lines (from the same redshift system). This figure’s distribution of points seems to fall at least as far below the $|W_a - W_b| = \max(W_a, W_b)$ line as those in Charlton et al. (1997) Figure 5 for the close pair 1343+2640A/B. The points flagged by the three-legged crosses denote absorbers spanning all three KP sightlines (with $W_0 > 0.4\text{\AA}$). While this minimum W_0 selection guarantees that the points sit at least 0.4\AA below the $|W_a - W_b| = \max(W_a, W_b)$ line, it is significant that those objects which span all three sightlines appear to be the most uniform of any in the $S/N \geq 3.5$, uncontaminated, Ly- α -only sample. Separate from this

selection effect, one can still state that the most homogeneous, strong lines also span all three sightlines. This argues that these compose a well-defined class of objects and are not produced by random superposition. Furthermore, the uniformity in W_0 argues against these pairs being produced simply by clustering of smaller objects, but indicates some coherence in the H I distribution on $0.5\text{--}0.8\ h^{-1}\ \text{kpc}$ scales, such as sheets of gas, and not filaments on these scales.

4.8.7. *Distribution of N_{HI} among Anti-coincident Lines (Charlton et al. 1995, 1997)*

Charlton et al. (1995) present the shape of the distribution f of column densities of lines *not* participating in hits within close pairs (N_{ac}) as a sensitive discriminator of cloud shape e.g. disks versus spheres. This difference appears most strongly at the high N_{HI} end, where spheres show a sharp cutoff at a position dependent on the size of the clouds relative to S , whereas disks show a gradual reduction at all N_{HI} values, with only a slow change in the slope of $\log(f)$ versus $\log(N_{ac})$. Charlton et al. suggest this test for a set N_{HI} cutoff in the linestrength of the “missing” line. (Lines weaker than this can produce anticoincidences in neighboring sightlines.) We impose a cutoff $W_o > 0.3\text{\AA}$, which corresponds to $\log(N_{HI}/\text{cm}^{-2}) = 14.16$ for $b = 30\ \text{km s}^{-1}$. One then studies the distribution f of N_{HI} in the remaining line. We plot this function in Figure 6 for 0307-1931/32, 1517+2356/57 and the KP triplet. The distributions are renormalized to have the same number of lines at $\log(N_{HI}/\text{cm}^{-2}) = 13.5$, below which the sample is grossly incomplete. (1343+2640A/B has so few anti-coincident lines that f is poorly defined.) This results in a total of 18 anticoincident lines in 0307-1931/32, 17 in 1517+2356/57, and 41 from sightline pairs among the KP triplet.

The behavior of the anticoincident N_{HI} distribution in Figure 16 differs from that in Figure 2 of Charlton et al. The observed distribution f is broader and present at stronger

N_{HI} for closer QSO pairs than in wider pairs, opposite the behavior predicted for spheres or disks. It is less discrepant with the more gradual increase in strength with increasing S found in disks. It is also less discrepant with the behavior of lines in simulations (Charlton et al. 1997, Figure 7), but is not in good agreement.

This puzzling behavior may simply be due to small number statistics. The critical difference in the shape of f for disks versus spheres occur over the high N_{HI} tail containing only 1-10% of the lines. We need several times as many data to adequately test these predictions.

4.9. Metal-line Absorber Clustering

The data on these five QSOs, especially the KP triplet, now includes enough space probed with closely-spaced sightlines through the absorber distribution that one can begin to ask how C IV absorbers cluster in space, as measured by the cross-correlation of the absorber distribution between sightlines, as opposed to auto-correlating the distribution along single sightlines. The latter approach, which has been presented in many works, carries with it the danger that spatial clustering signals may be mixed with velocity correlations due to internal velocity splittings within isolated absorbing objects. This is circumvented in the case of sightline cross-correlations; multiple absorber redshifts per object simply are reflected in an increase in the number of correlation pairs equally on all scales, not just for small separations such as those internal to an absorber. Such an increase in pairs cancels in the two-point correlation function ξ .

Figure 17 shows the number of cross-correlation pairs, binned in relative velocity (as in Figure 6 for Ly α clouds) but in this case for all C IV absorbers identified for the KP triplet. The solid curve shows all such C IV pairs, and the dotted curve only those

pairs involving both absorbers in the “probable” or “definite” categories, with detected C IV $\lambda 1548$. The dashed curve in Figure 17 shows the same information, but for all C IV absorbers in the LB pair, Q0307-195 pair and KP triplet (where each sightline is cross-correlated only with its partners in the same pair or triplet). Q1343+2640 is excluded since its separation may be smaller than the size of individual C IV galaxy cross-sections, and Q0107-025 is at much lower redshift. The first 500 km s^{-1} bin in Figure 16 shows more pairs than any other except one (which shows nine at $14000 \text{ km s}^{-1} < \Delta v < 14500 \text{ km s}^{-1}$). Furthermore, the first 2000 km s^{-1} interval shows more pairs than any other 2000 km s^{-1} interval in the entire Δv range. The average number of pairs per 500 km s^{-1} bin is 1.97, so the Poisson probability of the first bin having the observed six pairs (or more) is 1.5%, and the probability of the first four bins having the observed 15 pairs is also 1.5%. The probability of the second observation given the first is 14%, so the signal in the first bin is most significant, as long as we consider the first bin to be uniquely special, a priori. (If we do not, there are approximately 100 such equivalent bins, so the probability of such a random occurrence in some bin is nearly unity.) There is no obvious substructure in Δv within the first bin, but the contribution from the triplet is due to a single cluster at $z \approx 2.243$. Specifically, the signal arises in the LB pair at $\Delta v = 233 \text{ km s}^{-1}$ and $z = 0.7376$, in the Q0307-195 pair at $\Delta v = 306 \text{ km s}^{-1}$ and $z = 2.0337$, and in the KP triplet at $\Delta v = 100, 261, 360, 490 \text{ km s}^{-1}$ at redshifts 2.2419, 2.2431, 2.2437 and 2.2451, respectively. This is the most statistically significant signal ever seen showing that C IV clustering exists on small scales within sightline cross-correlations. It corresponds to a two-point correlation function $\xi = 2.05_{-1.21}^{+1.82}$ (68% confidence limits, as for the Ly α ξ in §4.3), over proper separations of 220 to $720 h^{-1} \text{ kpc}$, approximately (for $q_o = 1/2$), neglecting the distance component along the line of sight. Including this component, it corresponds to distances up to about $1.05 h^{-1} \text{ Mpc}$. With $q_o = 1/2$, this would correspond to velocity differences as large as 690 km s^{-1} in the Hubble flow.

While the statistical significance of this C IV cross-correlation result is not large, it should be compared to the single-sightline auto-correlation function (Sargent, Steidel & Boksenberg 1988), which shows, for single-sightline splittings of $200 \text{ km s}^{-1} < \Delta v < 600 \text{ km s}^{-1}$ a two-point function of variously $\xi = 5.7 \pm 0.6$ or $\xi = 11.5 \pm 1.3$ depending on whether or not a cutoff of $W_o = 0.15 \text{ \AA}$ is imposed on C IV $\lambda 1548$ (in the second case), with both cases excluding lines within 5000 km s^{-1} of the QSO emission redshift. The first case is inconsistent with our data at the 2σ level, the second being even more inconsistent. Our sample is more heterogeneous, not being defined by a specific cutoff on W_o or Δv with respect to the emission redshift, but of the 38 C IV $\lambda 1548$, only 8 have $W_o < 0.10 \text{ \AA}$ and 14 have $W_o < 0.15 \text{ \AA}$. None of the lines contributing to the ξ signal are within 5000 km s^{-1} of the emission redshift. Our sample is closer to the second sample from Sargent et al. (1988), and is inconsistent with the results obtained from it. This suggests that some of the power in ξ seen by Sargent et al. is not due to spatial clustering, but to internal motion within absorbers.

Measuring structure on larger scales by cross-correlation of sightlines is interesting, and unprecedented for unbiased samples (except for the full-sky cross-correlational study of Crofts [1985] and the recent paper Williger et al. 1996). Tytler et al. (1987), Heisler, Hogan & White (1989) and Quashnock, Vanden Berk & York (1996) suggest structure up to $100 h^{-1} \text{ Mpc}$ comoving scales in their studies of single-sightline metal-line autocorrelations. This is consistent with the power we see at $\Delta v \approx 14000 \text{ km s}^{-1}$, but we would need a larger sample to be sure. In general, however, the cross-correlational technique is most interesting on smaller scales, where internal velocities may be important. (Or it may be interesting for obtaining very dense, random samples, as suggested for the Ly α forest in §4.2, or for studying certain pre-selected anomalies e.g. in the region around a close damper Ly α absorber pair: Francis et al. 1996, and the $\approx 100 \text{ Mpc}$ absorber cluster in the Tololo QSO sample near 1037-27: Ulrich & Perryman 1986, Jakobsen et al. 1986, Jakobsen, Perryman

& Cristiani 1988, Robertson 1987, Cristiani, Danziger & Shaver 1987, Sargent & Steidel 1987, Jakobsen & Perryman 1992, Dinshaw & Impey 1996.) We are in the process of acquiring more such QSO pair data to study the clustering properties of C IV absorbers on Mpc scales.

5. Discussion

Returning to the clustering behavior of Ly α forest, one should note that in both their contributions to large-scale and small-scale structure, the $W_o > 0.4\text{\AA}$ Ly α sample and weaker lines differ in their behavior. Both in the small-scale two point correlation function, and in the presence of large-scale underdensities, the $W_o > 0.4\text{\AA}$ sample reveals more significant features (see Figures 6 and 7) which are washed out in larger, lower W_o cutoff samples. This might lead one to believe that these two populations are distinct. There is some evidence contradicting this, however, in that our original data from Q1343+2640A/B includes some lines weaker than $W_o = 0.4\text{\AA}$, and these also show signs of being associated with large absorbers. Whereas the entire $S/N > 3.5\sigma$ sample shows 11 hits and four misses, the $W_o > 0.4\text{\AA}$ subsample (see Table 8), once removed, leaves $N_h = 3$ and $N_m = 4$ for the remaining $W_o < 0.4\text{\AA}$ lines (typically $0.2\text{\AA} < W_o < 0.4\text{\AA}$, albeit not complete to $W_o = 0.2\text{\AA}$). This implies that these weaker absorbers have a median predicted radius $R = 63 h^{-1}$ kpc (assuming unclustered, constant radiused spheres, and with 95% confidence bounds $35 h^{-1} \text{ kpc} < R < 146 h^{-1} \text{ kpc}$), which, while possibly smaller than the size in the $W_o > 0.4\text{\AA}$ sample, still indicates absorbers that are much larger than the visible size of galaxies, and within about a factor of 2.5 of the size of low column-density H I galaxy halos at low z (Lanzetta et al. 1995). Compared to C IV absorbers as well (Steidel 1991, Paper I), these are still large absorbers.

It is apparent, however, that the $W_o > 0.4\text{\AA}$ absorbers are large enough, at least in

two dimensions, to span the gap between the triplet sightlines, while the weaker lines may not. It is interesting then, at this point, to examine the differences between those objects spanning all three sightlines and those $W_o > 0.4\text{\AA}$ clouds which do not. Of the five $W_o > 0.4\text{\AA}$ triple-hit objects, we note that two are associated with C IV absorbers, while another probably is. Furthermore, of the two that are not, one occurs at the same redshift of KP 79, the $z = 2.183$ QSO some $1.5 h^{-1}$ Mpc away from the triplet sightlines (in proper coordinates). In the rest of the $W_o > 0.4\text{\AA}$ Ly α sample, only 17 out of 144 absorbers have detected C IV absorption. These two populations are discrepant at the 3σ level. Absorbers with strong C IV may be associated with larger objects than strong Ly α absorbers without strong C IV. The average velocity spacing between these groups of lines corresponds to $35 h^{-1}$ Mpc (with $q_o = 1/2$), roughly the scale of sheets between the voids in the $z \approx 0$ galaxy distribution. This correspondence echoes a suggestion long ago by Oort (1981) that Ly α absorbers correspond to superclusters. These data suggest something rather different, that a small subsample may detect sheet-like structures on such scales. It is not clear to us that such structures are evident the current numerical simulations of the Ly α forest, nor that they necessarily should be given the small volumes simulated by these models.

6. Conclusions

The strongest results indicated here are that the redshift correspondences between Ly α absorbers in closer sightline pairs persists for proper separations up to $0.5\text{--}0.8 h^{-1}$ Mpc for lines stronger than $W_o = 0.4\text{\AA}$. There is an indication that the shape of the clouds responsible for this signal is not very elongated (aspect ratio $a < 4$, probably). There is weaker evidence, however, of expansion of these clouds with the Hubble flow in a way consistent with sheets or disks, and evidence of sheets of relatively uniform gas density spanning $0.5\text{--}0.7 h^{-1}$ Mpc transverse separations. This suggests that at least a large fraction

of high column density absorbers arise in expanding sheets. While we do not have such a measurement for weaker lines, there is data from Q1343+2640A/B (Paper I) that indicates that $0.2\text{\AA} \lesssim W_o < 0.4\text{\AA}$ clouds are probably at least $35\ h^{-1}$ kpc in radius (95%) confidence and probably closer to $63\ h^{-1}$ kpc in radius, still very large compared to the luminous size of galaxies and probably C IV absorbers.

Despite the strong leverage in redshift with the inclusion of the LB pair and Q0107-0234/0107-0235 and Q1026-0045A/B, the evidence for any evolution on the size of $W_o > 0.4\text{\AA}$ Ly α absorbers is not significant.

Our theoretical models to which the small-scale structure data are compared here are intentionally crude. Detailed comparison with numerical models incorporating hydrodynamics and ionization, as well as gravity, at high redshift lead to poor agreement in some cases and better in others, perhaps due to absence of clustering power on scales comparable to the simulation box size. It would appear that our current data may be inconsistent with the long filaments ($a \geq 10$) that are produced in these models, but detailed comparison of model and observation on as close a corresponding, quantitative basis as possible are required to minimize the systematic errors involved in analyzing the two forms of data differently.

C IV absorbers are shown to cluster in space as well as velocity on small scales ($\lesssim 1\ h^{-1}$ Mpc) for the first time in this paper, and while this signal is weak, it seems inconsistent with the same sort of measurement via single-sightline two-point correlation measurements. The simplest explanation for this difference is additional splittings within the absorbers themselves on velocity scales up to $600\ \text{km s}^{-1}$. This is hard to explain as the internal motions within galaxy halos (Sargent et al. 1988), but may indicate large velocity flows due to non-gravitational acceleration of gas, perhaps by shocks caused by star formation processes,

With the exception of strong clustering seen on sub-Mpc scales, and some indication of large, smooth sheets of gas, none of the new conclusions from these data is stronger than about 3σ , and many more indications are less certain than this. This calls for more QSO sightline pairs on the scale of separations less than about $1 h^{-1}$ Mpc proper separation. Since most of these will be at lower redshift than even the KP triplet, it also calls for UV sensitive instrumentation on large telescopes. (However, if the behavior of only stronger lines is non-random, higher S/N data will reveal no new effects.) In the long term, both practical developments seem likely, but are the limiting factors at present.

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Figure 1: the spectrum (in units proportional to photoelectrons as a function of wavelength in Angstroms) for Q1623+2651A (KP 76). The detected absorption lines are indicated by tickmarks extending downwards from the counts=0 line, and the dashed line indicates the standard deviation in counts per wavelength bin (typically $0.76\text{\AA}/\text{bin}$ in the top two panels and 0.72 in the bottom panel).

Figure 2: the spectrum for Q1623+2653 (KP 77), shown as for Figure 1.

Figure 3: the spectrum for Q1623+265B (KP 78), shown as for Figure 1.

Figure 4: the spectrum for 1517+2357 (LB9605), flux calibrated in units of $\text{erg s}^{-1} \text{ cm}^{-1}$, but otherwise shown as for Figure 1. The wavelength interval per bin ranges from 0.36\AA below 2230\AA , to 0.51\AA for $2230\text{\AA} < \lambda < 3270\text{\AA}$, to 0.49\AA for $3270\text{\AA} < \lambda < 3594\text{\AA}$, to 0.76\AA above 3594\AA .

Figure 5: the spectrum for 1517+2357 (LB9612), shown as for Figure 4.

Figure 6a: the Ly α forest two-point velocity cross-correlation function for all three sightline pairs among KP 76, 77 and 78, plotted as a histogram of the number of pairs in 50 km s^{-1} bins versus velocity difference Δv . The solid bars indicate pairs where both Ly α lines are stronger than rest equivalent width $W_o = 0.8\text{\AA}$. The densely shaded, lightly-shaded and unshaded bars show the same function for samples with $W_o > 0.4\text{\AA}$, 0.2\AA and 0.1\AA , respectively. The random pair count level for each of the W_o levels, as $\Delta v \rightarrow 0$, is indicated by the four dark tickmarks on the left edge of the graph.

Figure 6b: as in Figure 6a, but for LB9605 and LB9612.

Figure 7a: the number of Ly α forest lines stronger than $W_o = 0.4\text{\AA}$ found in 15 , 30 and $45 h^{-1} \text{ Mpc}$ wide bins (bottom solid curve, dashed curve and top solid curve, respectively) along the combined sightlines to KP 76, 77 and 78. The bins are stepped in redshift by $1/4$ of each bin width. Note the depressions in line counts at $z \approx 2.08$ and $z \approx 2.37$, referred to

in the text and indicated by the dark tickmarks.

Figure 7b: the same as in Figure 7b, but for lines stronger than $W_o = 0.1\text{\AA}$.

Figure 8: the foreground proximity effect for each QSO in the KP triplet, expressed as the number of lines per unit z as a function of redshift. The crosses shown the z bin width and the 1σ errors in the number of lines per bin as a function of mid-bin z . The dashed slanted line shows the mean number of lines per unit z , $n_\gamma(z)$, from a large sample of many sightlines. The solid curve shows $n_p(z)$, the expected number of lines once the ionization of foreground QSOs is included. A background ionizing flux density of $J_{21} = 0.1$ is assumed.

Figure 9: shows the same information as in Figure 8, but for LB9612.

Figure 10: the inferred cloud radius R (and 1σ confidence intervals) from a model assuming uniformly-sized, unclustered spherical clouds, as a function of QSO pair sightline separation S . The data from this paper for the four largest S pairs is shown, along with that of Q1343+2640A/B (Paper II), Q0107-0234/0107-0235 (Dinshaw et al. 1995) and Q0307-1931/0307-1932 (Shaver et al. 1983). All points must sit above the solid diagonal line if they show a significant detection, as $R > S/2$ in order for such clouds to span the sightlines. The best linear fit to $R(S)$ is shown by the dotted line for all six pairs, and by the dashed line once the lowest z pair Q0107-0234/0107-0235 is excluded.

Figure 11a: a contour plot of the probability P_{ab} of a cloud intercepting both the KP 76 and 77 sightlines if it is a cylinder of cross-sectional radius R and aspect ratio $a = l/2R$ for cylinder length l .

Figure 11b: as in Figure 11a, but for the probability P_{abc} of a cloud intercepting all three sightlines KP 76, 77 and 78.

Figure 12a: the measured values and 68% confidence intervals for P_{ab} , P_{ac} , P_{bc} and P_{abc} plotted on the same contours as those shown in Figure 11.

Figure 12b: the measured values and 68% confidence intervals for P'_{ab} , P'_{ac} , P'_{bc} and P_{abc} plotted on the same contours as those shown in Figure 11.

Figure 13: the measured values and 68% confidence intervals for probabilities P_{ab} , P_{ac} , P_{bc} , P'_{ab} , P'_{ac} , P'_{bc} and P_{abc} as a function of spherical cloud radius.

Figure 14: a cumulative histogram plot of the shear velocity v_{max} inferred for the four objects spanning the KP triplet sightlines as a function of v_{max} , along with the expected plots of the same quantity expected for sheets expanding in the Hubble flow according to three Freidman cosmological models.

Figure 15a: a comparison of linestrengths within the Ly α forest of 0307-1931/32 (proper separation of $231 h^{-1}$ kpc) showing the difference in rest equivalent width $|W_A - W_B|$ for hits within 200 km s^{-1} versus the strength of the stronger of the two lines. All Ly α line detections stronger than 3.5σ are considered. Error bars are $\pm 1\sigma$.

Figure 15b: a plot similar to Figure 15a, but for the KP triplet, taken one QSO pair at a time. Due to the density of points, no error bars are shown, but errors are much smaller than in Figure 15a, typically the size of the round symbols. The three-legged crosses mark lines involved in objects which span all three sightlines.

Figure 16: the distribution of anticoincident lines (all lines stronger than 3.5σ detections, but missing a neighbor stronger than $W_o = 0.3\text{\AA}$ within 200 km s^{-1} in the adjacent sightline). In the case of the KP triplet, each sightline pair is considered individually, Rest equivalent width has been converted to N_{HI} by assuming thermal widths of $b = 30 \text{ km s}^{-1}$, and the distributions are normalized to be equal at $\log(N_{HI}/\text{cm}^{-2}) = 13.5$.

Figure 17: the C IV $\lambda 1548$ absorber two-point velocity cross-correlation function for three different samples, plotted as a histogram of the number of pairs in 200 km s^{-1} bins versus velocity difference Δv . The dotted bars indicate only those pairs composed of “definite”

or “probable” C IV λ 1548 absorbers among the three KP triplet sightlines, while the solid bars indicate pairs including “possible” KP triplet absorbers. The dashed bars include pairs from Q1517+2357/1517+2356 and Q0307-1931/0307-1932 (Shaver et al. 1983).

Table 1. Absorption Lines in KP 76

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3319.05	3317.83-3320.11	1.26	5.08	
3329.50	3326.19-3333.03	3.65	11.21	Ly β @ 2.24601
3341.56	3339.87-3342.91	0.83	3.98	
3350.38	3348.99-3352.03	1.57	7.75	
3356.49	3355.07-3358.11	1.00	5.57	
3398.83	3396.11-3401.44	0.70	4.26	
3421.52	3418.92-3423.48	1.08	8.95	
3444.22	3442.48-3446.28	0.80	7.87	
3459.10	3455.40-3463.00	3.48	28.51	
3473.76	3470.60-3476.68	2.39	23.76	
3489.34	3487.32-3490.94	2.14	14.90	
3492.46	3490.94-3494.16	2.02	13.87	Ly β @ 2.40488?
3495.76	3494.93-3497.97	1.39	10.24	
3510.53	3508.61-3511.75	0.67	6.81	
3513.17	3511.75-3515.45	0.78	7.97	
3522.83	3521.53-3523.81	0.28	4.63	
3530.28	3526.85-3533.69	1.39	15.66	Ly β @ 2.44175?
3539.68	3537.49-3542.05	0.71	9.91	
3545.31	3543.90-3546.70	0.29	4.01	Si III λ 1206 @ 1.93850?
3552.88	3551.17-3554.21	0.25	4.36	
3556.04	3554.21-3558.01	1.13	19.63	
3571.37	3567.89-3574.73	3.00	51.07	Ly α @ 1.93778?
3579.17	3577.00-3581.30	0.26	3.66	

Table 1—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3585.40	3583.85-3586.89	0.28	6.28	
3594.73	3592.22-3596.78	1.11	22.26	
3606.45	3605.14-3608.18	0.33	7.07	
3629.26	3627.18-3630.27	0.88	12.23	
3632.31	3630.27-3634.78	1.79	24.88	
3648.17	3646.94-3649.22	0.36	7.67	
3665.74	3662.14-3669.74	2.08	28.54	
3674.90	3672.78-3677.34	1.40	25.36	
3685.26	3683.42-3687.23	0.36	6.96	
3691.25	3689.51-3692.55	0.12	4.67	
3698.20	3695.59-3700.91	2.17	38.95	
3704.03	3701.67-3706.23	0.38	6.57	
3715.88	3712.31-3717.49	2.62	41.12	
3718.34	3717.49-3720.67	1.38	21.62	
3725.59	3723.71-3727.51	0.49	10.04	
3735.58	3734.35-3737.39	0.38	8.20	
3754.77	3751.83-3757.15	1.15	20.50	Si III λ 1206 @ 2.11212
3762.44	3758.67-3764.75	0.79	13.26	
3770.51	3768.55-3772.35	0.22	4.55	
3775.13	3773.20-3776.00	0.22	4.61	
3783.50	3779.95-3787.56	4.32	75.49	Ly α @ 2.11228
3790.19	3788.32-3792.12	0.33	6.83	
3799.45	3797.44-3801.24	0.23	4.78	

Table 1—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3810.12	3808.50-3811.71	0.24	4.99	
3814.78	3812.64-3817.20	2.06	42.91	
3819.87	3817.96-3821.76	0.63	13.01	
3831.23	3829.62-3833.84	0.21	4.38	
3837.03	3834.68-3841.52	1.88	32.37	
3850.95	3849.12-3852.16	0.42	9.75	
3854.04	3852.16-3855.96	1.14	26.00	
3860.88	3859.76-3862.04	0.18	4.98	
3870.98	3868.12-3872.85	2.21	42.77	
3874.25	3872.85-3875.72	1.52	29.51	
3884.97	3883.33-3885.54	0.37	7.69	
3887.40	3885.54-3889.41	1.23	25.17	
3893.54	3892.01-3895.05	0.13	3.99	
3897.72	3897.01-3899.29	0.20	6.01	
3903.20	3901.57-3904.61	0.26	6.83	
3909.79	3907.65-3910.69	0.23	5.90	
3916.30	3913.73-3919.05	0.61	12.57	Si III λ 1206 @ 2.24600
3922.41	3920.57-3924.37	0.36	8.80	
3929.23	3926.65-3931.21	0.33	7.19	
3934.34	3932.55-3936.15	0.16	3.62	Si II λ 1260 @ 2.11198
3939.80	3938.05-3940.56	1.19	19.29	
3945.20	3940.56-3948.69	5.84	94.70	Ly α @ 2.24529
3952.09	3950.21-3953.25	0.40	10.39	

Table 1—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3959.61	3957.05-3961.61	1.18	28.46	
3968.25	3964.65-3972.25	1.96	39.03	
3978.20	3975.30-3979.86	0.20	4.59	
3986.74	3985.18-3988.22	0.18	4.92	
3991.43	3989.74-3992.15	0.33	6.02	
3995.08	3992.15-3997.34	1.36	24.71	
4000.30	3999.14-4000.89	0.23	5.59	
4003.03	4000.89-4004.94	0.84	20.22	
4008.79	4006.46-4010.80	0.95	17.57	
4011.85	4010.80-4013.30	0.49	9.18	
4015.61	4014.06-4017.10	0.13	3.57	
4026.90	4024.70-4029.26	1.44	37.18	
4036.02	4033.82-4037.08	0.74	13.36	
4038.07	4037.08-4038.92	0.69	12.44	
4040.72	4038.92-4042.94	1.47	26.52	
4051.23	4049.02-4052.82	0.19	4.91	
4054.42	4052.82-4055.63	0.43	8.90	
4057.25	4055.63-4059.66	0.58	11.92	
4064.97	4062.70-4067.26	1.20	30.32	
4068.60	4067.26-4069.63	0.30	6.21	
4071.21	4069.63-4073.35	0.45	9.52	
4078.98	4077.15-4080.19	0.22	3.71	
4087.73	4084.75-4089.84	0.65	12.38	

Table 1—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4092.52	4089.84-4094.63	0.83	15.78	
4100.97	4099.95-4102.23	0.13	4.60	
4104.86	4103.75-4106.03	0.22	8.27	
4107.39	4106.03-4109.07	0.20	6.38	
4113.71	4111.35-4115.91	0.26	7.42	Si III λ 1206 @ 2.40438?
4129.79	4125.79-4132.63	0.87	21.05	
4136.64	4134.91-4137.33	1.26	32.32	
4139.13	4137.33-4141.91	2.86	73.43	Ly α @ 2.40481?
4142.33	4141.91-4143.27	0.43	10.99	
4146.47	4144.80-4148.49	0.16	5.61	C I λ 1277 @ 2.24642
4153.24	4151.63-4155.43	0.45	16.00	C II λ 1334 @ 2.11213, part Si III λ 1206 @ 2.441?
4157.93	4156.19-4159.49	0.57	17.92	
4160.34	4159.49-4161.51	0.31	9.75	
4163.89	4162.27-4166.08	0.41	15.49	
4170.53	4168.36-4171.40	0.14	5.74	
4175.51	4173.68-4177.48	0.26	10.62	
4180.60	4179.00-4181.15	0.89	29.40	
4183.17	4181.15-4185.83	3.29	108.69	Ly α @ 2.44104?
4186.17	4185.83-4187.73	0.20	6.61	
4190.49	4187.73-4191.05	0.35	10.09	
4194.31	4191.05-4195.67	2.05	58.26	
4196.28	4195.67-4199.86	0.91	25.91	
4202.12	4199.86-4204.08	0.58	16.41	

Table 1—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4212.70	4210.92-4213.96	0.07	4.18	
4338.04	4335.57-4340.89	0.61	16.58	Si IV λ 1393 @ 2.11248
4366.05	4363.70-4368.26	0.26	6.68	Si IV λ 1402 @ 2.11245
4818.38	4816.07-4821.87	1.13	13.04	C IV λ 1548 @ 2.11224
4826.44	4824.04-4829.11	0.57	6.99	C IV λ 1550 @ 2.11228
5025.72	5023.22-5027.56	0.45	5.44	C IV λ 1548 @ 2.24617

Table 2. Absorption Lines in KP 77

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3247.00	3241.50-3254.36	5.87	9.02	Ly α @ 1.67095?
3287.58	3285.98-3289.18	1.29	7.18	
3339.64	3337.54-3342.08	1.29	6.29	
3351.14	3349.64-3352.66	1.23	6.66	part Ly γ @ 2.4453 ($< 0.3\text{\AA}$)
3356.40	3354.93-3357.96	1.15	6.40	
3404.59	3402.57-3406.35	0.90	8.44	
3421.17	3419.21-3422.99	0.59	5.60	
3453.35	3450.97-3455.51	0.86	8.77	
3466.38	3464.58-3468.36	0.46	5.59	
3476.57	3474.41-3478.95	0.65	7.92	
3487.22	3485.75-3487.96	0.64	5.92	Ly β @ 2.39977
3490.17	3487.96-3493.32	1.48	13.71	
3500.37	3497.10-3503.90	1.48	14.45	Ly α @ 1.87937, part Ly β @ 2.40966
3509.78	3507.68-3512.22	1.06	13.03	O VI $\lambda 1031$ @ 2.40199?
3519.64	3518.27-3522.05	0.35	4.50	
3525.56	3524.20-3527.82	0.98	14.69	
3529.20	3527.82-3531.35	0.60	8.97	O VI $\lambda 1037$ @ 2.40126?
3533.94	3531.35-3532.97	0.72	10.77	Ly β @ 2.44532
3546.28	3544.74-3547.76	0.71	10.15	
3552.50	3550.03-3554.57	1.78	20.58	Ly β @ 2.46341?
3557.89	3556.84-3559.10	0.96	14.71	
3563.93	3562.13-3565.91	1.51	19.97	Ly β @ 2.47456?
3571.65	3568.94-3574.23	1.86	24.61	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3577.52	3576.50-3579.52	0.30	5.29	
3586.58	3584.82-3588.60	0.42	7.16	Si III λ 1206 @ 1.97271
3591.81	3590.11-3593.13	0.20	3.74	
3596.91	3594.65-3599.18	0.84	14.28	
3601.17	3599.18-3602.96	0.65	12.03	
3609.22	3606.74-3611.13	2.06	23.44	artifact
3612.94	3611.13-3613.90	1.96	22.31	
3614.96	3613.90-3617.33	2.15	24.45	Ly α @ 1.97364
3619.79	3618.13-3621.33	0.39	4.41	Ly β @ 2.52902
3625.85	3624.89-3627.13	0.51	7.77	
3629.43	3627.13-3630.94	0.91	13.97	
3635.67	3634.72-3636.99	0.18	4.28	
3638.80	3636.99-3640.02	0.37	7.99	
3656.69	3655.10-3658.17	0.17	3.63	
3659.14	3658.17-3659.91	0.20	3.62	
3661.25	3659.91-3662.70	0.36	6.30	
3667.23	3665.73-3670.27	0.53	9.26	
3676.04	3673.29-3678.58	0.70	11.12	
3682.77	3679.34-3686.15	1.12	16.54	
3697.59	3694.46-3700.51	1.33	22.94	
3708.47	3704.29-3711.70	5.39	80.89	Ly α @ 2.05056
3713.97	3711.70-3717.91	3.78	56.71	Ly α @ 2.05508
3726.45	3723.96-3728.49	0.87	18.58	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3737.13	3734.54-3739.84	0.86	17.09	
3749.76	3748.15-3751.93	0.44	9.92	
3755.73	3754.20-3756.47	0.25	7.38	
3760.82	3758.74-3761.77	0.24	6.20	
3764.61	3762.52-3765.55	0.23	5.77	
3769.54	3767.81-3771.60	1.37	35.88	
3777.99	3773.30-3780.51	0.47	8.43	
3782.51	3780.67-3783.80	1.08	18.47	
3785.77	3783.80-3788.23	1.66	28.36	
3789.97	3788.99-3790.84	0.38	6.64	
3792.31	3790.84-3793.60	0.65	11.21	
3794.43	3793.50-3795.79	0.41	7.18	
3799.15	3797.39-3800.59	0.33	5.70	
3808.74	3807.14-3810.54	1.03	18.89	
3812.31	3810.54-3813.94	1.00	18.51	
3816.16	3813.94-3818.47	1.33	21.74	
3820.32	3818.47-3823.02	1.06	17.37	
3827.99	3824.53-3831.34	1.93	39.05	part Mg I λ 2026 @ 0.888
3835.22	3833.60-3837.38	0.58	14.54	
3843.07	3840.41-3845.70	2.95	76.37	Ly α @ 2.16128?
3848.08	3846.46-3850.24	0.15	3.66	
3854.75	3853.26-3857.05	0.26	6.34	
3862.69	3860.83-3864.04	1.12	19.08	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3864.75	3864.08-3865.48	0.59	10.06	
3868.96	3865.48-3872.17	2.80	47.84	
3875.26	3873.68-3876.71	0.16	4.25	
3881.01	3879.73-3882.00	0.13	3.91	
3888.76	3883.60-3890.30	0.37	8.39	
3896.11	3894.10-3898.64	0.37	8.39	
3902.42	3900.15-3903.93	0.24	5.99	
3907.29	3905.44-3908.47	0.39	10.88	
3916.78	3914.52-3918.30	0.16	4.01	
3934.36	3933.42-3936.45	0.14	4.05	
3938.99	3937.20-3940.98	0.92	24.72	
3944.24	3941.74-3946.43	2.56	53.56	Ly α @ 2.24450
3947.21	3946.43-3949.30	0.91	18.98	
3953.49	3951.57-3955.35	0.13	3.52	
3961.25	3959.13-3962.91	0.47	12.98	Fe III λ 1122 @ 2.52887?
3965.67	3962.91-3966.94	0.18	5.31	
3970.59	3968.21-3973.38	1.37	30.64	
3973.91	3973.38-3975.01	0.26	5.77	
3983.81	3980.90-3986.20	0.21	4.78	
3990.11	3988.62-3990.66	0.75	17.22	
3992.97	3990.66-3995.43	3.13	72.43	
3997.69	3995.43-3999.97	1.12	27.84	
4007.77	4004.50-4010.55	1.32	29.86	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4014.75	4012.82-4016.60	0.21	5.45	
4025.53	4022.65-4027.95	0.94	22.15	
4031.76	4030.97-4032.27	0.15	3.50	
4034.56	4032.27-4037.02	0.67	14.21	
4039.68	4038.53-4041.56	0.22	6.25	Fe II λ 1144 @ 2.52829?
4046.53	4044.58-4048.93	0.34	8.69	
4050.19	4048.93-4052.10	0.18	4.58	
4054.77	4052.90-4056.68	0.39	9.96	
4059.97	4057.44-4062.73	0.91	21.36	
4073.36	4070.29-4076.34	2.17	54.42	
4082.34	4079.37-4085.42	0.89	20.28	
4088.44	4086.93-4090.71	0.31	8.49	
4094.72	4093.74-4096.76	0.12	3.57	
4099.01	4097.52-4100.04	0.38	8.09	
4102.34	4100.04-4104.32	0.85	18.01	Si III λ 1206 @ 2.40020
4107.56	4105.83-4110.36	0.55	15.16	
4111.01	4110.36-4112.60	0.13	3.53	
4133.41	4128.52-4136.01	3.25	69.73	Ly α @ 2.40011
4136.31	4136.01-4138.35	0.37	7.96	C IV λ 1548 @ 1.67169
4145.02	4142.13-4148.94	2.16	53.01	Ly α @ 2.40966?
4149.75	4148.94-4151.21	0.44	10.46	
4152.88	4151.21-4154.23	0.24	7.57	
4156.98	4155.74-4158.77	0.17	5.35	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4160.34	4158.77-4161.79	0.25	8.22	
4166.65	4164.82-4168.60	0.40	11.81	
4170.71	4168.60-4173.14	0.55	14.89	
4178.48	4176.80-4180.70	0.45	12.15	
4182.18	4180.70-4182.81	0.59	11.20	
4187.85	4182.81-4191.09	4.70	89.66	Ly α @ 2.44489
4192.03	4191.09-4194.31	1.37	26.07	
4198.75	4198.09-4199.49	0.35	7.22	
4201.15	4199.49-4202.13	0.79	16.18	
4204.39	4202.13-4206.41	1.80	37.06	
4210.44	4208.68-4211.82	1.31	30.78	Ly α @ 2.46347?, part NV λ 1238 @ 2.399
4213.52	4211.82-4217.17	1.61	37.96	
4217.49	4217.17-4219.26	0.14	3.59	
4220.94	4219.26-4221.19	0.36	8.48	
4223.24	4221.19-4227.88	2.99	70.28	Ly α @ 2.47408?
4228.12	4227.88-4229.09	0.16	3.67	
4243.30	4241.19-4244.97	0.23	8.59	
4250.65	4248.76-4251.41	0.20	5.23	
4254.95	4251.41-4257.83	0.91	24.46	
4263.28	4260.85-4264.64	0.27	10.81	
4269.02	4266.90-4271.02	0.59	19.09	
4271.92	4271.02-4272.95	0.26	8.60	
4275.03	4273.71-4277.49	0.49	20.30	

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4282.32	4279.76-4285.05	1.01	39.32	
4289.89	4287.32-4292.61	1.53	66.01	Ly α @ 2.52883
4426.76	4424.95-4428.73	0.21	5.44	Fe II λ 2344 @ 0.88838
4458.66	4456.71-4463.18	0.57	9.48	C IV λ 1548 @ 1.87990
4465.50	4463.18-4468.49	0.29	4.88	C IV λ 1550 @ 1.87952
4483.60	4482.42-4484.69	0.21	4.00	Fe II λ 2374 @ 0.88826
4499.04	4496.79-4502.08	0.39	7.46	Fe II λ 2382 @ 0.88816
4602.24	4601.14-4603.41	0.20	4.06	C IV λ 1548 @ 1.97264
4610.36	4609.46-4610.97	0.16	3.56	C IV λ 1550 @ 1.97294
4722.70	4720.49-4723.82	1.16	11.26	C IV λ 1548 @ 2.05044
4726.20	4723.82-4729.38	2.48	24.08	C IV λ 1548 @ 2.05270
4730.25	4729.38-4731.23	0.68	6.60	C IV λ 1550 @ 2.05025
4734.12	4731.23-4736.42	2.00	19.45	C IV λ 1550 @ 2.05275
4781.45	4779.89-4782.78	0.31	5.80	
4859.91	4858.12-4861.74	0.57	10.75	Mn II λ 2576 @ 0.88597
4884.74	4882.75-4886.37	0.29	5.42	Fe II λ 2586 @ 0.88844
4894.87	4892.89-4897.24	0.62	11.48	Mn II λ 2594 @ 0.88663, part C IV λ 1548 @ 2.1616
4902.93	4900.86-4904.48	0.32	6.37	Fe II λ 2600 @ 0.88562, part C IV λ 1550 @ 2.1616
4909.92	4907.38-4911.73	0.38	7.11	Mn II λ 2606 @ 0.88375
5023.13	5021.11-5024.73	0.27	5.12	C IV λ 1548 @ 2.24449
5032.21	5030.52-5034.15	0.26	4.79	C IV λ 1550 @ 2.24497
5265.80	5262.33-5269.57	1.11	15.97	C IV λ 1548 @ 2.40124
5273.76	5272.47-5274.29	0.28	3.52	C IV λ 1548 @ 2.40637?

Table 2—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
5277.33	5274.29-5280.04	1.88	23.81	Mg II λ 2786 @ 0.88722, C IV λ 1550 @ 2.401
5281.42	5280.04-5282.61	0.53	6.74	C IV λ 1550 @ 2.40567?
5292.78	5289.13-5296.37	1.40	20.12	Mg II λ 2803 @ 0.88790
5303.67	5302.17-5305.79	0.54	10.48	
5331.72	5329.70-5333.32	0.24	4.54	C IV λ 1548 @ 2.44381
5387.28	5384.75-5389.82	0.32	5.49	Mg I λ 2852 @ 0.88831
5464.10	5460.21-5468.51	0.55	7.05	C IV λ 1548 @ 2.52932
5472.96	5468.51-5477.60	0.40	5.49	C IV λ 1550 @ 2.52918

Table 3. Absorption Lines in KP 78

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3347.05	3345.07-3348.85	1.86	4.42	
3355.71	3354.14-3357.17	1.59	4.41	
3362.52	3360.19-3365.48	1.50	3.53	
3394.26	3391.95-3396.49	1.05	4.44	part Ly δ @ 2.5739
3439.71	3438.08-3441.00	1.25	5.66	
3441.94	3441.00-3443.24	0.92	4.15	part Ly γ @ 2.5394
3453.39	3451.69-3455.47	1.77	8.84	Ly γ @ 2.55091, part Ly β @ 2.3653?
3457.30	3455.47-3458.49	1.15	6.42	
3460.64	3458.49-3461.51	0.87	4.81	
3469.66	3471.35-3471.06	0.77	4.74	part Ly γ @ 2.567, part C III λ 977 @ 2.5512
3473.36	3471.06-3475.59	1.26	7.78	part Fe λ 1122 @ 2.0942
3476.61	3475.59-3478.13	0.57	3.55	Ly γ @ 2.57479
3487.49	3485.71-3489.50	0.77	5.38	
3517.15	3515.20-3518.99	1.05	9.06	part Ly β @ 2.4274?
3526.92	3525.03-3528.82	0.98	8.91	
3529.89	3528.82-3531.08	0.48	5.49	Ly β @ 2.44137?
3539.24	3537.89-3540.91	0.54	5.29	
3544.43	3543.18-3545.17	0.54	3.80	Ly β @ 2.45555?
3547.00	3545.17-3549.23	1.33	9.46	part Ly β @ 2.4580?
3557.77	3556.04-3559.82	0.63	5.57	
3562.52	3565.11-3563.59	0.36	3.84	
3566.16	3563.59-3567.38	0.86	9.19	
3568.67	3567.38-3569.65	0.48	5.08	

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3571.56	3569.65-3573.43	1.67	15.68	Ly α @ 1.93794?
3576.59	3573.43-3578.53	0.42	3.90	
3586.13	3583.50-3589.19	0.81	5.09	
3591.30	3589.19-3594.60	0.56	3.51	
3596.47	3594.60-3597.63	1.30	13.33	
3599.95	3598.38-3601.41	0.99	9.87	
3604.41	3601.41-3606.70	2.35	19.79	
3609.90	3608.97-3611.24	0.58	7.62	
3624.03	3622.58-3624.71	0.51	3.67	
3627.71	3624.71-3629.61	2.25	16.24	Ly α @ 1.98412, part Ly β @ 2.5365?
3630.57	3629.61-3631.65	1.13	8.20	Ly α @ 1.98498, Ly β @ 2.53963
3634.92	3632.95-3636.70	0.73	6.34	Ly β @ 2.54377?
3640.07	3636.70-3644.51	1.39	12.03	Ly β @ 2.54879? part Fe III λ 1122 @ 2.24275
3642.82	3636.95-3644.51	1.06	9.17	Ly β @ 2.55147
3657.13	3655.10-3658.95	1.33	13.38	
3659.54	3658.95-3661.15	0.44	4.37	Ly β @ 2.56777
3667.22	3664.93-3667.90	0.90	9.66	Ly β @ 2.57526
3669.52	3667.90-3671.73	0.83	8.86	
3680.35	3678.54-3681.68	0.73	7.25	part C II λ 1036 @ 2.5513
3683.74	3681.68-3686.10	1.12	11.64	
3692.59	3690.64-3695.17	1.17	15.46	
3698.41	3695.17-3701.22	2.45	30.43	Ly α @ 2.04228
3705.54	3707.80-3713.30	0.53	6.58	

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3715.67	3714.08-3717.10	0.71	12.02	
3721.37	3717.86-3724.66	3.18	49.91	Ly α @ 2.06117?
3732.70	3730.71-3734.77	2.04	24.42	Si III λ 1206 @ 2.09383
3735.62	3734.77-3737.52	0.84	10.09	
3740.60	3737.10-3741.30	0.35	4.18	
3744.54	3742.06-3747.35	0.84	10.56	
3762.09	3756.42-3767.01	10.56	91.42	Ly α @ 2.09466
3774.66	3773.06-3776.55	1.33	14.29	
3778.14	3776.55-3779.86	1.10	11.86	
3786.19	3782.89-3788.94	2.78	35.78	
3794.23	3792.90-3796.70	0.35	3.79	
3807.42	3706.10-3810.00	0.47	5.10	
3815.20	3811.62-3819.18	4.48	55.77	
3837.41	3834.31-3840.36	2.80	40.10	
3857.10	3854.72-3860.02	1.36	21.47	part Si II λ 1190 @ 2.24013
3870.54	3867.58-3873.63	2.44	39.45	
3880.52	3878.92-3881.74	0.54	8.15	
3882.88	3881.74-3884.21	0.50	7.70	
3893.54	3891.02-3895.56	0.94	14.13	
3898.94	3896.31-3901.61	2.00	29.20	part Si II λ 1260 @ 2.0934
3907.74	3905.39-3909.92	2.29	34.30	
3911.24	3909.92-3912.19	0.54	9.66	Si III λ 1206 @ 2.24181
3913.94	3912.19-3914.81	0.67	8.15	

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3916.87	3914.81-3919.00	1.59	19.24	
3924.59	3922.78-3926.43	0.75	12.77	
3926.96	3926.43-3927.36	0.21	3.64	
3932.29	3930.34-3934.88	1.39	20.73	
3940.01	3934.88-3944.71	5.98	69.50	Ly α @ 2.24102
3947.28	3946.22-3948.49	0.55	5.61	
3954.12	3949.49-3956.05	0.27	3.61	
3960.19	3957.65-3962.80	0.37	5.29	
3966.93	3964.37-3968.65	1.08	15.09	
3969.47	3968.65-3971.17	0.52	7.22	
3975.53	3974.50-3977.00	0.33	4.08	
3981.61	3977.00-3982.52	0.53	6.52	
3984.41	3982.52-3984.41	0.36	4.45	part Fe III λ 1122 @ 2.5497
3987.69	3984.41-3990.08	1.16	14.39	
3994.11	3991.59-3996.88	0.63	9.52	
4002.23	4000.66-4003.69	0.34	6.56	
4013.45	4012.01-4015.03	0.20	3.77	Fe III λ 1122 @ 2.57537, N V λ 1238 @ 2.23973
4016.52	4015.03-4018.06	0.23	4.39	N V λ 1238 @ 2.24221
4024.74	4023.35-4026.37	0.30	5.72	
4028.88	4027.13-4030.49	0.58	8.08	part N V λ 1242 @ 2.2418
4032.12	4030.49-4033.18	0.63	8.91	
4038.49	4036.20-4040.74	2.23	39.73	
4042.83	4040.74-4044.94	1.35	17.78	

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4046.16	4044.94-4048.30	0.78	10.30	
4053.59	4050.57-4057.20	2.22	28.12	
4058.30	4057.20-4060.40	0.70	8.82	
4067.55	4064.94-4069.48	0.24	3.91	
4075.51	4074.01-4076.61	0.56	8.61	
4078.38	4076.61-4080.06	0.90	13.87	
4084.51	4082.33-4088.38	0.64	12.31	Si II λ 1260 @ 2.24059
4091.04	4088.38-4093.67	1.42	22.47	Ly α @ 2.36526? part Fe III λ 1144 @ 2.5754?
4096.59	4093.67-4098.97	0.39	6.04	
4100.93	4098.97-4102.38	0.90	13.09	
4103.98	4102.38-4105.77	1.00	14.48	
4112.58	4111.07-4114.09	0.50	9.98	
4116.14	4114.09-4117.87	0.30	4.32	
4119.67	4117.87-4120.90	0.35	6.67	
4129.03	4126.94-4131.48	1.50	25.91	C II λ 1334 @ 2.09399
4137.98	4136.02-4139.14	1.16	15.32	part C I λ 1277 @ 2.23977
4140.03	4139.14-4143.58	0.89	11.77	C I λ 1277 @ 2.24137
4150.27	4148.12-4151.90	1.13	15.38	
4154.04	4151.90-4156.44	1.48	20.12	
4162.04	4159.46-4164.15	2.17	26.12	
4166.56	4164.15-4170.05	1.83	22.05	Ly α @ 2.42738?
4175.04	4173.07-4176.85	0.97	16.41	
4178.61	4176.85-4179.88	0.78	14.11	

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4183.60	4181.39-4185.93	1.74	9.56	Ly α @ 2.44139?
4192.34	4190.46-4195.00	0.42	7.03	
4201.01	4198.02-4202.35	2.39	38.43	Ly α @ 2.45572?
4203.80	4202.35-4206.34	2.59	41.75	Ly α @ 2.45801?
4209.14	4207.85-4210.88	0.27	5.58	
4223.29	4221.47-4225.10	0.47	7.06	
4227.09	4225.10-4229.03	0.52	7.78	part Si II λ 1190 @ 2.55094, Si II λ 1304 @ 2.24071
4243.75	4242.10-4245.30	0.34	5.09	
4250.10	4248.69-4252.28	1.06	13.94	
4253.23	4252.28-4254.15	0.48	6.38	
4256.17	4254.15-4257.76	1.07	14.09	
4262.15	4260.79-4263.81	0.88	19.16	
4266.85	4265.32-4269.10	0.95	18.83	
4273.85	4272.89-4275.15	0.73	18.15	
4279.32	4277.42-4281.96	1.30	18.13	
4284.34	4281.96-4287.25	1.32	18.40	part Si III λ 1206 @ 2.55105
4290.60	4288.05-4291.25	0.25	3.55	
4299.20	4297.08-4300.66	2.10	29.36	Ly α @ 2.53649?
4302.76	4300.66-4305.95	3.02	42.19	Ly α @ 2.53941
4307.68	4305.95-4309.94	1.64	22.93	Ly α @ 2.54346?
4313.56	4310.69-4315.08	2.46	41.27	Ly α @ 2.54830? part Si III λ 1206 @ 2.5753 Si IV λ 1393 @ 2.09492
4316.91	4315.08-4319.77	2.96	49.62	Ly α @ 2.55105

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4323.45	4320.60-4323.32	0.22	3.62	C II λ 1334 @ 2.23967
4326.46	4323.32-4329.60	0.53	8.86	C II λ 1334 @ 2.24193
4332.03	4329.60-4334.53	1.90	31.82	Ly α @ 2.56694
4335.54	4334.53-4337.16	0.77	12.94	
4340.19	4338.67-4342.45	1.40	34.14	Si IV λ 1402 @ 2.09401
4345.51	4343.21-4348.53	1.61	33.71	Ly α @ 2.57458
4349.27	4348.53-4350.01	0.52	8.66	
4356.58	4354.55-4358.79	0.88	14.65	
4359.60	4358.79-4361.36	0.32	5.33	
4362.96	4361.36-4364.39	0.46	9.00	
4365.09	4364.39-4365.50	0.23	4.40	
4369.82	4365.50-4373.46	2.47	60.17	Ly α @ 2.59458 ^a
4376.87	4374.30-4378.85	0.09	3.50	
4379.78	4378.75-4381.02	0.21	8.10	
4385.64	4383.29-4387.82	0.64	19.59	
4475.62	4473.27-4477.81	0.32	6.05	Si II λ 1260 @ 2.55089
4515.75	4513.35-4517.74	0.99	11.54	Si IV λ 1393 @ 2.23999
4518.70	4517.74-4520.64	0.48	5.62	Si IV λ 1393 @ 2.24211
4544.50	4541.50-4545.89	0.36	5.03	Si IV λ 1402 @ 2.23966
4547.72	4545.89-4549.80	0.47	6.61	C IV λ 1548 @ 1.93742? Si IV λ 1402 @ 2.2196
4559.46	4557.60-4560.80	0.35	4.93	
4622.26	4620.70-4623.60	0.62	5.87	C IV λ 1548 @ 1.98557
4630.08	4628.67-4631.57	0.48	4.59	C IV λ 1550 @ 1.98566, Si II λ 1304 @ 2.5496

Table 3—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
4710.35	4709.07-4711.25	0.35	4.18	C IV $\lambda 1548$ @ 2.04246
4718.36	4716.80-4720.10	0.37	5.27	C IV $\lambda 1550$ @ 2.04258
4739.29	4736.60-4741.67	0.72	5.88	C IV $\lambda 1548$ @ 2.06116? part C II $\lambda 1334$ @ 2.5513
4789.77	4786.11-4791.82	1.89	9.81	C IV $\lambda 1548$ @ 2.09376
4792.93	4791.82-4794.34	1.03	5.33	C IV $\lambda 1548$ @ 2.09580
4797.06	4794.34-4800.23	1.85	9.57	C IV $\lambda 1550$ @ 2.09333
4801.37	4800.23-4803.97	0.66	3.53	C IV $\lambda 1550$ @ 2.09611
4949.39	4947.39-4951.01	0.40	4.17	Si IV $\lambda 1393$ @ 2.55112, part Si II $\lambda 1526$ @ 2.2419
4981.25	4979.98-4982.88	0.38	4.38	Si IV $\lambda 1393$ @ 2.57398, Si IV $\lambda 1402$ @ 2.55101
5014.99	5012.58-5016.22	1.62	9.93	C IV $\lambda 1548$ @ 2.23923
5018.86	5016.22-5022.15	3.48	21.37	C IV $\lambda 1548$ @ 2.24173
5023.38	5022.15-5024.69	1.29	7.94	C IV $\lambda 1550$ @ 2.23927
5027.21	5024.69-5030.69	2.49	15.24	C IV $\lambda 1550$ @ 2.24174
5168.70	5166.87-5171.22	0.58	5.47	Al II $\lambda 1670$ @ 2.09357
5497.83	5495.73-5500.07	0.56	5.14	C IV $\lambda 1548$ @ 2.55111

^a If this line at 4369.82Å is Ly α , one should expect to see Ly β at 3687.04Å. There is a marginally detected line there, with $W_{obs} \approx 0.3$ Å, so 4369.82Å is plausibly consistent with being Ly α .

Table 4. Absorption Lines in LB 9605

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
1669.79	1668.39-1670.90	0.81	3.79	Al II λ 1670 @ -0.00060
1691.70	1690.62-1692.77	0.93	4.92	part Ly γ @ 0.738
1697.99	1696.72-1699.23	0.97	5.15	
1714.77	1713.21-1716.44	1.21	6.17	Ly α @ 0.41056?
1724.98	1723.97-1725.77	0.65	3.85	
1731.96	1731.14-1732.58	0.46	3.54	
1743.65	1741.90-1745.13	0.65	3.63	Ly β @ 0.69992?
1780.02	1779.20-1780.63	0.42	3.72	
1782.94	1780.99-1784.93	1.57	9.39	Ly β @ 0.73823
1793.71	1792.11-1794.97	0.96	6.41	
1803.33	1801.79-1805.02	1.10	6.97	
1838.92	1837.29-1840.52	0.64	3.77	
1843.96	1842.67-1845.18	0.72	5.18	
1856.93	1855.58-1858.45	0.82	5.52	
1885.09	1883.19-1886.78	0.85	5.44	
1894.79	1893.95-1895.74	0.58	4.97	
1926.51	1924.79-1928.37	0.98	7.14	part Ly δ @ 1.028
1950.10	1948.81-1951.68	0.80	5.72	Ly ϵ @ 1.07943
1960.38	1959.57-1961.01	0.40	3.93	Ly γ @ 1.01574
1974.04	1970.69-1977.14	1.99	10.31	part Ly δ @ 1.080, part Ly γ @ 1.028
1980.19	1978.58-1981.81	0.79	5.40	part C III λ 977 @ 1.028?
1986.06	1985.39-1987.19	0.97	8.64	
2017.73	2016.23-2018.74	0.68	5.80	Ly β @ 0.96713?

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2022.45	2020.18-2024.12	1.47	10.05	Ly γ @ 1.07956
2030.74	2030.22-2031.29	0.51	6.05	
2044.21	2043.48-2044.92	0.66	7.69	
2065.47	2064.64-2066.53	0.93	7.26	
2067.77	2066.53-2069.30	1.10	8.57	part Ly β @ 1.01592, Ly α @ 0.70020?
2079.90	2077.91-2081.86	1.37	12.44	Ly β @ 1.02774
2091.59	2090.46-2092.97	0.60	6.47	O VI λ 1031 @ 1.02689
2103.69	2102.66-2104.81	0.36	4.24	O VI λ 1037 @ 1.02743
2106.07	2104.81-2107.32	0.53	5.69	
2113.37	2110.90-2116.28	2.69	25.69	Ly α @ 0.73844
2122.67	2121.66-2123.81	0.32	3.87	
2133.16	2130.27-2135.29	1.69	15.81	Ly β @ 1.07967
2145.41	2144.25-2146.76	0.30	3.61	
2157.78	2156.09-2159.31	0.62	7.01	
2161.75	2161.11-2162.54	0.24	3.93	
2184.19	2182.98-2185.85	0.66	8.61	part Ly δ @ 1.301, C IV λ 1548 @ 0.41079?
2187.63	2186.57-2188.72	0.29	4.02	C IV λ 1550 @ 0.41067?
2219.94	2218.12-2222.07	1.36	17.02	Ly β @ 1.16427?
2222.95	2222.07-2223.86	0.38	6.49	
2231.24	2229.60-2233.46	0.63	7.43	
2238.26	2235.51-2240.62	0.64	6.91	Ly γ @ 1.30147
2249.23	2247.78-2250.34	0.26	3.60	Ly β @ 1.19283
2254.53	2253.41-2255.96	0.32	4.47	

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2273.37	2271.30-2275.91	0.75	7.91	
2278.59	2276.42-2280.51	1.03	11.39	
2284.17	2282.55-2285.62	0.37	4.62	
2306.76	2305.05-2308.12	0.41	4.36	
2342.94	2341.36-2344.43	0.39	4.29	Fe II λ 2344 @ -0.00054
2354.42	2353.12-2355.68	0.65	6.03	
2360.87	2359.26-2362.32	0.98	9.30	Ly β @ 1.30167
2367				no Ly limit ($\tau < 0.1$)
2373.83	2371.53-2376.64	0.88	6.29	Si III λ 1206 @ 0.96753?
2381.62	2379.71-2384.31	0.71	5.43	Fe II λ 2382 @ -0.00048
2386.86	2385.80-2389.40	0.71	5.60	part Ly 10 @ 1.596
2391.51	2389.43-2393.52	1.10	9.53	part Ly 9 @ 1.596, Ly α @ 0.96724?
2396.27	2394.69-2395.90	0.57	4.96	Ly 8 @ 1.59575
2403.82	2402.21-2405.79	0.62	5.68	Ly 7 @ 1.59529
2415.72	2414.49-2417.55	0.54	5.33	Ly 6 @ 1.59546
2422.54	2421.64-2423.69	0.42	4.94	Si IV λ 1393 @ 0.73814
2434.15	2432.89-2435.96	0.70	5.82	Ly ϵ @ 1.59559
2445.28	2443.63-2447.21	1.23	11.65	part Si II λ 1206 @ 1.028
2448.77	2447.72-2449.26	0.64	7.72	
2451.14	2449.26-2452.84	1.29	13.14	Ly α @ 1.01629
2455.94	2455.39-2456.42	0.40	6.30	
2463.15	2462.04-2463.46	0.40	3.54	
2465.33	2463.46-2468.18	2.39	21.31	Ly α @ 1.02796, part Ly δ @ 1.596

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2471.89	2471.25-2472.78	0.36	5.05	Ly δ @ 1.60269
2479.80	2478.41-2481.47	0.61	6.89	
2483.36	2482.50-2484.03	0.35	4.95	Fe I λ 2484 @ -0.00027
2490.79	2489.40-2492.90	0.48	6.84	Ly β @ 1.42833?
2524.37	2522.38-2526.43	1.52	12.03	part Fe I λ 2523 @ 0.000, Ly γ @ 1.59565
2528.85	2526.43-2532.61	2.41	19.05	Ly α @ 1.08021, part Ly γ @ 1.603
2539.93	2537.94-2541.30	0.36	4.54	
2558.29	2556.64-2559.71	0.64	8.05	
2577.64	2574.54-2580.17	1.13	11.21	part Mn II λ 2576 @ 0.000, part Ly β @ 1.513
2584.38	2582.21-2586.30	0.78	8.65	part Fe II λ 2586 @ 0.000
2592.94	2590.39-2595.00	0.58	6.35	Mn II λ 2594 @ -0.00061, O VI λ 1031 @ 1.51272
2598.41	2595.51-2600.62	1.11	12.14	part Ly 7 @ 1.805, part Fe II λ 2600 @ 0.000
2607.95	2606.25-2609.14	0.92	6.63	Mn II λ 2606 @ 0.00057, part O VI λ 1037 @ 1.51341
2610.42	2609.14-2612.90	0.64	4.56	Ly 6 @ 1.80465
2612.98	2612.90-2614.41	0.64	4.61	Ly γ @ 1.68676
2617.23	2614.41-2620.05	1.27	9.11	Ly ϵ @ 1.80480, part Ly β @ 1.551?
2625.59	2622.10-2628.24	0.94	9.38	
2630.35	2628.24-2632.96	1.27	10.35	Ly α @ 1.16370?
2634.20	2632.96-2635.38	0.60	4.90	
2636.81	2635.38-2638.46	0.73	5.92	
2646.67	2645.11-2647.68	0.48	4.63	
2648.68	2647.68-2651.25	0.47	4.58	Ly β @ 1.58226? part Ly γ @ 1.725?
2662.63	2659.43-2664.36	2.31	23.15	Ly β @ 1.59586, part Ly δ @ 1.804

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2665.62	2664.36-2668.63	1.67	16.80	Ly α @ 1.19272
2670.99	2670.17-2672.72	0.76	11.20	Ly β @ 1.60401
2679.32	2676.81-2682.44	1.62	17.33	
2685.40	2684.49-2687.55	0.99	12.81	
2690.98	2689.09-2691.86	0.80	7.02	C IV λ 1548 @ 0.73813
2692.68	2691.86-2693.76	0.75	6.59	Ly β @ 1.62515?
2696.06	2693.76-2698.29	1.59	13.98	part C IV λ 1550 @ 0.738
2699.88	2698.80-2700.81	0.31	4.33	
2701.95	2700.81-2702.38	0.38	5.27	Ly δ @ 1.84493
2712.95	2711.59-2714.15	0.40	4.58	
2719.32	2717.73-2720.79	0.27	3.87	
2727.88	2725.91-2730.00	1.21	17.18	Ly γ @ 1.80491
2734.80	2733.20-2736.40	0.22	4.15	
2737.81	2736.40-2739.71	0.22	4.22	
2740.62	2739.71-2741.25	0.28	5.41	
2750.55	2747.38-2753.08	1.68	16.99	Ly β @ 1.68157?
2754.56	2753.08-2756.08	0.72	7.31	Ly β @ 1.68548
2765.67	2763.24-2768.35	0.86	10.87	Ly γ @ 1.84377
2770.97	2769.37-2772.44	0.59	9.66	Ly β @ 1.70148?
2781.60	2780.11-2783.18	0.32	4.91	
2787.30	2785.74-2788.80	0.33	5.05	
2794.73	2792.90-2795.65	1.11	10.99	Mg II λ 2796 @ -0.00058, Ly β @ 1.72465?
2797.78	2795.65-2800.04	1.75	17.31	Ly α @ 1.30143

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2801.97	2800.04-2804.15	1.50	14.81	part Mg II λ 2803 @ -0.00056
2805.81	2805.17-2807.21	0.37	6.63	
2809.95	2808.75-2811.30	0.33	5.56	Ly β @ 1.73948?
2817.59	2815.91-2819.49	0.39	5.49	Ly β @ 1.74693?
2821.96	2820.51-2823.58	0.27	4.05	Fe III λ 1122 @ 1.51393, Ly β @ 1.75116?
2827.21	2826.13-2828.18	0.28	4.86	part Si IV λ 1393 @ 1.028?
2843.59	2841.99-2845.57	0.29	3.76	Ly β @ 1.77228?
2851.00	2849.66-2852.21	0.25	4.05	Mg I 2852 @ -0.00069
2860.76	2858.86-2862.44	0.49	6.99	Ly β @ 1.78902?
2869.61	2868.00-2871.32	0.33	4.53	
2876.94	2874.20-2879.83	1.76	22.90	Ly β @ 1.80479, part Fe II λ 1144 @ 1.514
2894.06	2891.59-2896.19	0.59	8.15	Ly β @ 1.82195
2916.24	2914.60-2918.18	0.68	11.26	Ly β @ 1.84311
2923.25	2921.76-2924.21	0.62	9.88	
2924.71	2924.21-2925.74	0.33	5.19	
2926.44	2925.74-2927.85	0.22	3.51	
2930.97	2929.94-2931.99	0.19	3.84	
2935.48	2934.54-2936.59	0.37	7.42	
2944.10	2943.24-2944.77	0.22	4.87	
2952.50	2950.40-2954.49	1.07	16.80	Ly α @ 1.42870?
2963.21	2959.09-2966.25	1.00	10.64	
2977.97	2976.48-2979.03	0.33	5.13	
2988.55	2987.22-2989.77	0.30	4.57	

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2999.63	2995.40-3002.56	0.92	9.34	
3003.71	3002.56-3005.62	0.26	3.71	
3051.53	3050.62-3052.67	0.23	3.67	
3055.27	3053.18-3057.27	1.26	18.05	Ly α @ 1.51324
3077.11	3075.17-3079.26	0.43	5.31	
3093.03	3091.53-3094.60	0.49	6.91	
3101.24	3098.69-3102.53	1.55	16.44	Ly α @ 1.55105?
3103.51	3102.53-3105.85	1.17	12.38	
3127.73	3125.79-3129.37	0.71	8.84	
3131.51	3129.37-3133.98	0.85	9.39	
3139.51	3136.02-3143.41	2.84	23.37	C IV λ 1548 @ 1.02784, Ly α @ 1.583
3145.19	3143.41-3146.76	1.29	10.63	C IV λ 1550 @ 1.02814
3156.05	3153.41-3158.87	3.30	35.75	Ly α @ 1.59614
3159.63	3158.87-3161.08	0.86	9.34	
3163.73	3161.08-3165.98	1.43	13.54	Ly α @ 1.60246
3167.11	3165.98-3168.75	0.72	6.79	Si II λ 1260 @ 1.51274
3191.61	3188.18-3195.85	1.55	15.44	Ly α @ 1.62539?
3203.26	3201.99-3204.54	0.49	7.33	
3210.14	3209.15-3211.66	0.29	3.86	C I λ 1277 @ 1.51333?
3215.93	3214.69-3217.72	0.46	5.81	
3241.63	3240.42-3242.44	0.34	5.42	
3249.00	3248.49-3249.50	0.24	4.93	
3259.47	3257.07-3262.61	2.00	23.05	Ly α @ 1.68121?

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3264.57	3262.61-3266.64	1.53	16.16	Ly α @ 1.68541
3283.39	3282.25-3284.85	2.28	6.64	Ly α @ 1.70089?
3285.62	3284.85-3286.61	1.20	3.55	
3310.86	3309.40-3312.80	1.12	4.58	Ly α @ 1.72349?
3318.61	3317.65-3319.59	0.86	4.77	
3330.30	3328.80-3331.22	1.05	5.82	Ly α @ 1.73948?
3339.33	3337.53-3341.89	1.97	9.65	Ly α @ 1.74690?
3345.10	3343.83-3346.26	0.98	6.45	Ly α @ 1.75165?
3365.96	3365.17-3367.11	0.61	5.21	
3370.41	3369.05-3371.96	1.15	8.48	Ly α @ 1.77247?
3391.24	3389.41-3393.85	1.68	11.46	Ly α @ 1.78961?
3394.46	3393.85-3396.69	0.87	5.93	C IV λ 1548 @ 1.19257
3404.54	3403.18-3405.87	0.47	3.70	Si III λ 1206 @ 1.82183?
3407.19	3405.87-3407.74	0.71	5.60	
3409.70	3407.74-3413.17	2.57	20.12	Ly α @ 1.80454
3420.62	3419.48-3421.42	0.20	3.64	
3429.73	3427.72-3431.60	1.07	16.15	Ly α @ 1.82127
3434.43	3433.54-3435.48	0.21	4.38	
3440.20	3438.39-3442.27	0.61	10.87	
3449.11	3447.37-3450.77	0.21	3.80	
3456.64	3454.88-3458.76	1.53	31.53	Ly α @ 1.84340
3485.66	3483.97-3487.37	0.35	5.75	
3568.98	3567.38-3570.29	0.31	4.09	C IV λ 1550 @ 1.30142?

Table 4—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3756.50	3749.18-3763.14	1.05	6.25	continuum error?
3891.41	3889.75-3892.79	0.42	6.45	C IV λ 1548 @ 1.51350
3897.89	3896.59-3898.87	0.27	4.59	C IV λ 1550 @ 1.51351
3928.13	3926.98-3929.26	0.22	3.97	
3933.11	3931.54-3934.58	0.22	3.57	Ca II λ 3934 @ -0.00042
4019.20	4017.39-4021.19	0.29	4.39	C IV λ 1548 @ 1.59604

A line at 4404.56Å is uncertain due to rapid change in continuum in the C IV emission line.

Table 5. Absorption Lines in LB 9612

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
1687.67	1686.32-1688.83	1.47	4.05	part Ly γ @ 0.737
1781.15	1779.91-1782.42	1.16	4.28	Ly β @ 0.73648
1807.35	1806.81-1807.89	0.62	3.73	
1884.37	1883.55-1885.34	1.54	6.36	
1901.40	1900.76-1902.56	0.99	4.05	
2111.21	2109.47-2112.70	1.68	5.86	Ly α @ 0.73666, part Ly β @ 1.060
2212				no Ly break ($\tau < 0.1$)
2240.36	2238.57-2242.15	1.12	4.65	Ly 8 @ 1.42687 ^a
2247.65	2246.25-2249.31	1.02	4.94	Ly 7 @ 1.42668 ^a , C III λ 977 @ 1.30050
2275.30	2273.86-2276.93	1.09	5.01	Ly ϵ @ 1.42620 ^a
2304.33	2303.01-2305.56	1.02	4.95	Ly δ @ 1.42627 ^a
2360.20	2358.23-2361.81	1.99	5.65	part Ly γ @ 1.426 ^a , part Ly β @ 1.300?
2381.71	2380.22-2382.78	1.07	3.51	Fe II λ 2382 @ -0.00044
2484				Ly break ($\tau \approx 2.1$)
2496.44	2495.00-2498.20	0.83	6.90	Ly β @ 1.435? Ly blend @ 1.724
2501.54	2500.39-2502.44	0.48	4.02	part Ly β @ 1.439? Ly blend @ 1.724
2505.10	2503.46-2506.53	1.00	7.91	part Ly 10 @ 1.72486, Ly α @ 1.060
2508.90	2508.06-2509.60	0.67	6.50	Ly 9 @ 1.72421
2515.14	2513.69-2516.25	0.53	4.70	Ly 8 @ 1.72452. part Fe I λ 2523 @ 0.000 ^b
2523.64	2521.87-2525.45	0.79	6.18	Ly 7 @ 1.72465
2536.15	2534.66-2538.24	0.90	7.54	Ly 6 @ 1.72485
2555.07	2553.06-2557.16	1.04	8.42	part Ly ϵ @ 1.724, part Ly 7 @ 1.759
2567.90	2566.36-2569.43	0.57	5.18	Ly 6 @ 1.75896

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2586.78	2583.75-2589.88	1.98	14.04	part Ly δ @ 1.724, part Ly ϵ @ 1.759, part Fe II λ 2586 @ 0.000, Ly α @ 1.127
2599.39	2598.06-2601.13	0.70	6.56	Fe II λ 2600 @ 0.000
2609.03	2608.29-2609.83	0.37	4.44	
2613.77	2612.38-2615.45	0.48	4.41	
2619.67	2617.50-2621.59	1.16	10.20	part Ly δ @ 1.759, Ly β @ 1.55398
2625.88	2624.15-2627.72	1.22	11.86	part Ly ϵ @ 1.800
2632				Ly break ($\tau \approx 0.6$)
2632.74	2630.79-2635.40	1.12	9.59	part N V 1238 @ 1.127?
2649.61	2648.18-2651.76	0.97	9.76	Ly γ @ 1.72443
2655.15	2653.80-2657.38	0.54	5.53	Ly 10 @ 1.88807, part Si III λ 1206 @ 1.127?
2658.71	2657.38-2660.45	1.00	7.42	Ly 9 @ 1.88688, part Ly δ @ 1.800
2661.77	2660.45-2663.10	0.75	5.59	C III λ 977 @ 1.72450
2664.44	2663.10-2666.59	0.76	5.65	Ly 8 @ 1.88625
2674.28	2671.70-2676.81	1.85	20.36	part Ly 7 @ 1.886
2683.94	2682.95-2684.86	0.64	4.92	Ly γ @ 1.75973
2686.52	2684.86-2688.00	1.16	8.88	Ly 6 @ 1.88641
2689.89	2688.00-2692.16	1.48	11.37	C IV λ 1548 @ 0.73743, part Ly β @ 1.624?
2694.20	2692.16-2696.25	0.78	8.10	C IV λ 1550 @ 0.73733
2707.00	2704.94-2709.03	0.85	9.67	Ly ϵ @ 1.88653
2716.75	2714.66-2718.32	0.85	6.32	Ly β @ 1.64862? C I 1277 @ 1.12704
2719.27	2718.32-2720.66	0.52	3.85	
2723.33	2720.66-2725.40	1.00	7.42	part Ca I λ 2722 @ 0.000, part Ly γ @ 1.800

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2741.74	2740.23-2743.80	1.11	14.42	Ly δ @ 1.88682
2770.12	2767.84-2771.24	0.66	6.82	
2771.95	2771.24-2772.95	0.42	4.36	
2777.75	2776.02-2779.09	0.44	5.49	Ly β @ 1.70809?
2782.67	2781.65-2784.00	0.43	3.85	
2785.55	2784.00-2787.78	0.92	8.26	Ly β @ 1.71570?
2794.36	2791.36-2796.99	2.06	21.52	Mg II λ 2796 @ -0.00071, Ly β @ 1.72429, Ly α @ 1.300?
2802.11	2799.54-2804.66	1.09	11.13	Mg II λ 2803 @ -0.00051
2807.69	2805.68-2810.28	1.43	16.32	Ly γ @ 1.88698
2820.51	2818.98-2822.04	0.43	5.36	C III λ 977 @ 1.88683?
2830.90	2828.18-2833.29	0.85	9.04	Ly β @ 1.75991
2852.09	2850.68-2853.75	0.30	3.85	Mg I λ 2852 @ -0.00031
2871.73	2869.60-2873.69	0.97	10.40	Ly β @ 1.79971, Si IV λ 1393 @ 1.06000
2889.81	2887.50-2892.10	0.44	4.20	Si IV λ 1402 @ 1.06007
2899.14	2897.73-2900.28	0.52	6.90	Si II λ 1260 @ 1.30013
2906.12	2905.40-2907.95	0.30	4.06	
2929.82	2928.41-2930.98	0.86	7.51	
2935.00	2930.98-2938.12	2.97	25.94	Ly α @ 1.41431
2945.81	2943.75-2950.57	0.80	6.95	
2950.17	2950.57-2953.98	3.28	28.52	Ly α @ 1.42679 ^a
2960.28	2956.53-2963.18	2.53	28.20	Ly α @ 1.435? part Ly β @ 1.88604
2965.80	2963.69-2967.78	1.08	14.06	Ly α @ 1.43964? part Si II λ 1393 @ 1.127

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
2977.90	2975.45-2980.57	1.27	15.37	part O IV λ 1031 @ 1.886?
3001.81	3000.51-3003.07	0.25	3.76	
3026.33	3025.06-3027.61	0.29	4.17	
3044.47	3042.95-3045.51	0.47	5.86	
3063.32	3061.87-3065.06	0.69	6.23	
3066.52	3065.06-3068.01	0.58	5.21	
3082.73	3080.28-3085.40	0.76	7.53	
3104.97	3101.76-3108.41	2.27	22.81	Ly α @ 1.55412
3155.24	3153.92-3156.15	0.50	4.94	
3157.55	3156.15-3159.03	0.77	7.60	
3176.35	3174.38-3177.95	0.61	6.29	
3182.70	3180.51-3184.60	0.85	8.71	
3187.82	3185.62-3188.10	0.65	5.60	
3189.90	3188.10-3191.76	1.07	10.51	Ly α @ 1.62398? part C IV λ 1548 @ 1.060
3194.54	3192.78-3195.85	0.44	4.93	C IV λ 1550 @ 1.05996
3198.19	3196.88-3199.94	0.55	6.27	
3201.80	3200.97-3203.01	0.36	4.74	
3220.43	3218.22-3222.19	1.08	9.64	Ly α @ 1.64910?
3222.87	3222.19-3224.28	0.41	3.71	
3250.34	3248.99-3251.01	0.34	4.79	
3261.58	3258.58-3264.15	0.74	5.65	
3284.97	3283.22-3286.61	0.90	8.49	
3292.14	3289.04-3294.86	1.62	11.90	Ly α @ 1.70809? part C IV λ 1548 @ 1.127

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3297.33	3295.83-3297.85	0.58	3.78	C IV λ 1550 @ 1.12625
3300.55	3297.85-3303.59	3.04	19.73	Ly α @ 1.71500?
3311.46	3309.40-3313.77	2.29	20.52	Ly α @ 1.72398
3321.09	3319.10-3323.47	0.50	4.54	
3338.93	3338.01-3339.95	0.42	5.83	
3342.62	3341.89-3343.35	0.19	2.96	
3353.12	3351.11-3354.99	1.12	12.35	Ly α @ 1.75825
3365.81	3364.20-3367.10	0.71	6.80	Si IV λ 1393 @ 1.41492
3368.24	3367.10-3371.47	0.63	6.04	
3378.79	3378.26-3380.20	0.34	6.27	
3387.15	3386.50-3387.96	0.28	6.14	Si IV λ 1402 @ 1.41462
3391.61	3390.38-3392.81	0.34	6.38	
3395.06	3393.78-3396.20	0.43	8.36	
3397.38	3396.20-3398.63	0.28	5.35	
3403.36	3401.05-3405.42	2.03	33.77	Ly α @ 1.79958
3408.76	3407.36-3409.78	0.56	11.97	C II λ 1334 @ 1.55427
3414.38	3412.69-3415.60	0.36	7.06	part C I @ λ 1656 @ 1.060?
3439.59	3438.39-3440.82	0.18	4.34	
3455.79	3453.91-3457.30	0.35	7.86	
3466.93	3465.55-3468.45	0.22	5.86	
3471.76	3470.40-3473.30	0.46	12.34	
3480.08	3479.12-3480.63	0.18	4.29	C I λ 1277 @ 1.72468
3482.01	3480.63-3483.97	0.46	10.87	Si III λ 1206 @ 1.88604

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
3486.48	3484.94-3487.85	0.31	9.59	
3489.95	3488.34-3492.22	0.34	9.85	
3499.39	3497.07-3500.94	0.26	7.81	Mg II λ 2796 @ 0.25141?
3503.25	3500.94-3504.67	0.12	3.58	
3509.22	3506.76-3511.61	2.44	90.10	Ly α @ 1.88665, part Mg II λ 2803 @ 0.251?
3519.18	3516.46-3520.03	0.19	4.83	
3522.60	3520.03-3526.16	0.65	16.26	C I λ 1656 @ 1.12598
3562.26	3559.62-3564.95	0.17	4.85	C IV λ 1548 @ 1.30090?
3571.23	3569.80-3572.71	0.15	5.70	Mg I λ 2852 @ 0.25176?
3738.17	3735.51-3740.83	1.66	28.66	C IV λ 1548 @ 1.41452
3744.45	3741.59-3747.67	1.37	21.95	C IV λ 1550 @ 1.41457
3757.09	3754.50-3759.06	0.25	4.53	C IV λ 1548 @ 1.42674
3863.55	3861.64-3865.43	0.19	4.01	
3925.88	3923.18-3929.26	0.23	4.18	
3933.23	3930.78-3936.10	0.36	7.02	Ca II λ 3934 @ -0.00039
3954.45	3953.57-3955.85	0.17	4.17	C IV λ 1548 @ 1.55422
3960.58	3958.89-3961.93	0.13	3.61	C IV λ 1550 @ 1.55394
3968.30	3966.49-3969.53	0.14	3.51	Ca II λ 3969 @ -0.00033
4140.65	4138.96-4142.00	0.19	4.92	
4217.86	4215.70-4219.50	0.17	3.91	C IV λ 1548 @ 1.72436
4470.26	4466.44-4474.03	0.27	5.37	C IV λ 1548 @ 1.88739
4517.89	4515.27-4518.87	0.36	6.01	C I λ 1656 @ 1.72667?

Table 5—Continued

$\lambda_{vac}(mean)$	λ Range	W_{obs}	S/N	Comments
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^a The $z = 1.426$ system’s Ly β occurs at the Ly break at 2484Å. Ly 6 at 2258Å for $z = 1.426$ is marginally detected.

^b Fe I λ 2484 is also lost in Ly break at 2484Å.

^c The wavelength and strength of the 4517.89Å line are more uncertain than implied by the S/N given the uncertainty in the continuum on the C IV emission line.

Table 6. LY α SAMPLES FROM QSO TRIPLET AND PAIR

Parameter	KP 76	KP 77	KP 78	LB 9605	LB 9612
Sensitivity Ranges:^a					
z range, $W_o \geq 0.1\text{\AA}$	1.88-2.47	1.90-2.53	1.94-2.61	1.79-1.84	1.32-1.90 ^c
z range, $W_o \geq 0.2\text{\AA}$	1.78-2.47	1.78-2.53	1.82-2.61	0.73-1.84 ^b	1.06-1.90 ^d
z range, $W_o \geq 0.4\text{\AA}$	1.72-2.47	1.70-2.53	1.75-2.61	0.47-1.84	1.05-1.90
z range, $W_o \geq 0.8\text{\AA}$	1.68-2.47	1.65-2.53	1.70-2.61	0.36-1.84	0.50-1.90
Sample:^e 1) $\lambda_{rest}=1020\text{-}1220\text{\AA}$^f					
$\geq 0.1\text{\AA}$, $N_{lines, "pure"}$	54	60	60	34	30
$\geq 0.1\text{\AA}$, $N_{lines, contaminated}$	54	62	68	35	34
$\geq 0.2\text{\AA}$, $N_{lines, "pure"}$	33	39	40	26	17
$\geq 0.2\text{\AA}$, $N_{lines, contaminated}$	33	41	45	27	20
$\geq 0.4\text{\AA}$, $N_{lines, "pure"}$	17	19	21	15	6
$\geq 0.4\text{\AA}$, $N_{lines, contaminated}$	17	19	24	16	9
$\geq 0.8\text{\AA}$, $N_{lines, "pure"}$	5	8	7	4	3
$\geq 0.8\text{\AA}$, $N_{lines, contaminated}$	5	8	7	3	3
2) Extended $W_o \geq 0.4\text{\AA}$^g					
$N_{lines, "pure"}$	24	24	29	-	-
$N_{lines, contaminated}$	26	28	36	-	-

^aRange in z over which unresolved line is detected at 5.5σ . ^bMissing z range 1.689-1.756.

^cMissing z range 1.690-1.723. ^dPlus additional z range 0.834-0.900. ^eAlso described in text.

^fFor triplet, z overlap range is 2.02-2.47, with $\langle z \rangle = 2.25$; for pair, z overlap range is 1.44-1.84, with $\langle z \rangle = 1.65$.

^gFor triplet, z overlap range is 1.76-2.47, with $\langle z \rangle = 2.14$. Sample does not apply to pair.

Table 7. FOREGROUND QSO PROXIMITY EFFECT: PREDICTED VERSUS
OBSERVED DENSITIES OF $W_o > 0.1\text{\AA}$ LY α LINES

QSOs	Redshift Range	Number of Lines, n	Proximity Prediction $(\int wn_p dz)$	Null Model Prediction $(\int wn_\gamma dz)$	Observed Value $(\sum_{i=1}^n w_i)$	Variance $(\sum_{i=1}^n w_i^2)$
KP 76	2.175-2.191	2	0.150	0.163	0.166	0.014
KP 77	2.173-2.193 2.425-2.485	14	1.562	2.532	3.657	1.461
KP 78	2.173-2.193 2.435-2.574	23	4.038	7.708	7.561	3.679
KP triplet combined	(above ranges)	39	5.750	10.403	11.384	5.154
LB 9612	1.815-1.857	2	0.609	1.047	0.286	0.047
All 4 QSOs	(above ranges)	41	6.359	11.450	11.670	5.201

Table 8. Ly α CLOUD RADIUS ESTIMATES FROM QSO PAIRS

QSO Pair	Angular Separation ($''$)	Ly α z Range	S , Proper Separation ($h^{-1}kpc$)	N_h	N_m	95% Confidence Interval in R ($h^{-1}kpc$)	Median Radius, R ($h^{-1}kpc$)
1343+2640A/B	9.5	1.756-2.035	39-40	7	1	77-841	237
1025-0045A/B	36	0.830-1.438	149-154	1	5	95-306	148
0307-1931/32	56	1.690-2.122	226-236	4	12	165-434	246
0107-0234/35	86	0.481-0.952	301-364	4	6	286-918	501
1517+2356/57	102	1.390-1.830	425-438	3	28	226-429	283
1623+2651A/B	127	2.025-2.467	493-522	6	32	264-520	340
1623+2651A/53	147	1.958-2.467	571-604	8	26	323-757	461
1623+2653/51B	177	2.025-2.526	683-721	5	36	357-675	442











































